Development and Use of a Hybrid Electric Vehicle (HEV) Model for Interactive Customer Assessment of Sound Quality

INNOVATION REPORT

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ABSTRACT

With the increasing adoption and usage of *hybrid electric vehicle* (HEV) technologies, there is a growing recognition that attributes such as dynamics, driveability and refinement can have an adverse affect on customer acceptance. There are a number of new challenges associated with their refinement, in particular their sound quality. These issues include: understanding customers' perceptions of new sound sources, such as electric *motor/generators* (M/G) and electronic switching devices; reduced masking from the *internal combustion engine* (ICE); the effect that a more advanced control strategy can have on vehicle-level sound (both internally and externally); and the effect of new sound character on customer perception.

Given these new challenges for the sound quality of HEVs, the best approach for learning about perceptions needed to be determined. Interactive *noise, vibration and harshness* (NVH) simulation is well suited to further our understanding of these issues. The process for developing models for interactive NVH simulation of conventional vehicles is well established. However, research was necessary to both enhance this process for the creation of HEV models and to create new assessment methods. This report gives a brief overview of a project to deliver this.

The key stages were: classification of unique HEV operations; development of a HEV NVH model; validation of the NVH model to determine its suitability for interactive simulation; leading onto recommendations for the use of new HEV sound quality models for assessment.

An interactive HEV model has been successfully created and used in a number of newly created HEV sound quality evaluations. Three assessments were created and carried out which addressed new HEV related refinement issues of varying ICE masking, varying control strategy and the effect of added interior synthesized sound on customer perception. Key findings included: preference for reduced *internal combustion engine* (ICE) sound in the *Toyota Prius* and significant differences in perception of the same HEV, over the same drive cycle with varying initial battery state-of-charge (SoC). The process developed and carried out and learning achieved has been documented as a selection of flowcharts and can be used by OEMs or sound specialists as a means for improving HEV sound quality.

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This could have easily been my largest chapter if I was to mention all of those who have supported me along the way. All I can say is many thanks to you all, I'm forever grateful.

DECLARATION

I confirm that the work contained in this report is my own unless otherwise stated.

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John Poxon, 30th September 2009

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List of Acronyms and Abbreviations

Acronyms

2GWOT	2^{nd} gear wide open throttle
ADVISOR	ADvanced VehIcle SimulatOR
APU	Auxiliary power units
B&K	Brüel & Kjær
CVT	Continuously variable transmission
EM	Electric motor
EPA	Environmental Protection Agency
EV	Electric vehicle
HEV	Hybrid electric vehicle
HWFET	Highway Fuel Economy Cycle
ICE	Internal combustion engine
IMDS	Intermediate Manager Development Scheme
JLR	Jaguar & Land Rover
NEDC	New European Drive Cycle
NVH	Noise, vibration and harshness
RMS	Root mean square
SoC	State-of-charge
SoH	State-of-health
TfL	Transport for London
THS	Toyota hybrid system
WARPSTAR	WARwick Powertrain Simulation Tool for ARchitectures
WOT	Wide open throttle

Abbreviations

mph	miles per hour
RPM	revolutions per minute

1 Introduction

1.1 Background to HEVs

The competition between vehicles powered by electricity compared to those powered by *internal combustion engines* (ICEs) dates back to the 19^{th} century. Between 1890 and 1905 ICEs, *electric vehicles* (EVs), and steam powered cars were all marketed in the UK and United States (Berman, 2004). EVs were the market leader in the US at this time; mainly due to the works of electrical pioneers such as Thomas Edison and Nikola Tesla. However it soon became evident that the use of batteries in automobiles posed limitations in range, power and utility of EVs. Due to the energy advantages of petrol and diesel powered vehicles over battery operation; they became the dominant energy sources over the next 100 years. Many automotive companies began developing direct ICE vehicles, but some tried to combine the advantages of an EV with those of an ICE vehicle by creating the first hybrid vehicle concepts.

The first ever *hybrid electric vehicle* (HEV) was built in 1899 by Dr Ferdinand Porsche (*Lohner-Porsche Mixte Hybrid*), and there were several automotive companies who were beginning to sell HEVs in the early 1900s. HEVs did not last long as *Henry Ford* for one initiated the mass production of conventional ICE vehicles; making them widely available and affordable. In contrast, the price of the less efficient EVs continued to rise. During 1912, an electric roadster sold for $1,732, whilst a gasoline car sold for $547.

In recent times there has been a rise in global fuel prices in conjunction with diminishing oil supplies. These issues along with other occurrences such as more stringent legislation focused on lowering vehicle emissions have led to a shift to develop more eco-friendly vehicle options; with particular focus on HEV technologies. With advances in battery technologies and especially onboard computer systems, the option of a commercially viable HEV has become reality. A number of automotive companies now have one or more HEVs within their current or future vehicle programmes. From the initial introduction of the first *Toyota Prius* model in Japan 1997 (later introduced worldwide in 2001) there will be in excess of 30 commercial HEV models available by the end of 2011. Already there has been a shift towards the premium end of the market with the introduction of the *Lexus RX 400h* in early 2005 making it the world's first luxury HEV. With announcements already being made from Porsche (regarding the *Porsche Panamera Hybrid*) soon to be followed by other leading brands the perception of HEVs lacking character, performance and style is long gone.

HEV sales have not yet escalated in the UK; one of the reasons being that the emissions legislation passed in the US (particularly in California) has been far more stringent than anything in the UK to date. In Europe, diesel technologies have been more favourably received than in the US; with many people in the US still believing that diesel vehicles are noisy, smelly and underpowered compared to ICE equivalents (Berman, 2005). Diesels (in general) do not meet the emissions standards that even large V8 petrol engines do. The growing concern of global warming and attempts to reduce the amount of tailpipe $C0_2$ emissions are other issues which have increased the sales potential of HEVs. There are growing efforts to introduce a more energy efficient means of transport, and one effort lies with the inclusion of a congestion charge within London, UK. In March 2002 the *TransportAction PowerShift* (The Energy Savings Trust) a government funded initiative finalised its congestion charging scheme. The scheme was initiated in February 2003. The regulations of the scheme meant that drivers would have to pay a £5 daily (now £8 for non-exempt vehicles and £7 for fleet vehicles) congestion charge if they wanted to drive through central London between 7am and 6:30pm. The London congestion charge scheme exempts HEV drivers from paying this charge, as they are regarded as *green* vehicles due to low CO_2 emissions.

The *TransportAction PowerShift* was an initiative promoting cleaner motoring between 1996 and 2004. This initiative helped to promote cleaner motoring by offering a £1,000 grant to all first time buyers of all commercially released HEVs. A recent government led campaign has been 'Act on CO_2', with the aim of guiding people into reducing their carbon footprint. Through a supporting website it is possible to work out individual and/or household CO_2 emissions for the home, appliances and travel. The travel section supports the shift to HEVs and other eco-friendly vehicle options. Through such efforts the popularity and growth of HEVs and other eco-friendly vehicle technologies is likely to increase in the UK.

One of the key challenges for manufacturers of HEVs is the need to reduce the costs of the overall vehicle and technologies going into them. If the volume of HEV models developed goes up, the cost of production will begin to decrease. There are many aspects that can still be improved in order to make HEVs a more commercially viable option to the mass market including: a reduction in purchase price with technology improvements and increased production. Traditionally customers tend to have distrust for new technology; represented by a society's fear of change. There have been a number of studies into the techniques behind resisting change, and inspiring innovative creations (Metcalfe and Cantner, 2003; Clark, 1995). One key point highlighted in both texts is that technology continually needs to grow through the development of innovative products (e.g. HEVs) and the knowledge of the customer must also grow through creating the awareness and acceptance of such products. In relation to HEVs the initial reaction and acceptance throughout the world market has been an extremely positive one, especially in the United States. Both the *Honda Insight* and the *Toyota Prius* exceeded their original sales targets when initially released in the US. With the continual growth of HEV technologies in the worldwide market and potential for further research it is a great opportunity to be involved with the development of this technology.

HEVs will have a definite stronghold in the future of automotive development, due to the flexibility of the technology. The current configuration of HEVs (electric motor and ICE) is strongly influenced by legislation, but future hybrid technologies could move towards other options including: fuel cells and biodiesel. The regenerative braking energy is one example which conventional equivalents do not offer. Hybrid vehicle technologies will continue to develop over the next 10-20 years, in some form or another. The development of solutions to HEV problems now can be used as a platform for the next generation of vehicle technology advancements.

1.2 Focus of the Project

With the increasing adoption and usage of HEV technologies, there is a growing recognition that attributes such as: dynamics, driveability and refinement can have an adverse affect on customer acceptance. There are a number of new challenges associated with their refinement, in particular their sound quality. The introduction of HEVs has raised many new sound quality related issues which were not previously evident within conventional vehicle equivalents. There is therefore a need to improve the understanding of subjective assessment of HEVs, complementing the objectively focused decisions (currently more established) and aiding early engineering decisions as a result. The aim of the work covered in this report was to develop and trial the new assessment methods necessary to facilitate an enhanced understanding of HEV sound quality. Taking these new types of customer perception into account through a structured approach to sound quality assessment should ultimately lead onto suggestions for new best practice HEV design and then, improve the overall perception of the vehicle and the desirability of HEVs. Interactive *noise, vibration and harshness* (NVH) simulation as shown in this project is well suited to further the understanding of these issues. The process for developing models for interactive NVH simulation of conventional vehicles is well established. However, research was necessary to enhance this process for the creation and validation of HEV models. It was also necessary to develop and use new assessment methods for best–practice use by decision makers involved in the improvement of HEV refinement.

This project has been supported by *Brüel & Kjær (B&K)*; a world leading OEM manufacturer/supplier of sound and vibration solutions. Their customer base covers a wide range of fields including: automotive, aerospace and government agencies. One of the other key companies involved in this project has been *Sound Evaluations Ltd*; a team of sound & vibration engineers with interactive NVH simulation experience and technology/software development.

The following section provides a brief review of the individual reports (submissions) submitted in partial fulfilment of the Engineering Doctorate; explaining the reasons and aims of each submission, work documented within each and the overall story they collectively contribute towards.

Chapter 2 focuses on the identification of the need to improve HEV sound quality assessment. Prior to this work the sound quality evaluation process was well established for conventional vehicle developments, with the introduction of HEVs bringing new specific issues which were not previously well covered/considered during this process.

With a review of practice prior to this work and new specific HEV refinement issues being raised by customers, enthusiasts and from initial academic work it was clear that changes could and needed to be made. Within this section these new specific HEV refinement issues, project aim and the reasons for choosing interactive *noise, vibration and harshness* (NVH) simulation as a suitable application for this work are all discussed.

Chapter 3 discusses the methodology created and carried out for developing a HEV model for interactive sound quality assessments. The work covered within this process includes: identification of uniquely HEV operations (sound sources, control strategies, etc.), plan for recordings (instrumentation and representative drive cycle selection) and creation and validation of a HEV model. In order to trial the new approaches, a real-life case study with a *Toyota Prius* was undertaken.

Within chapter 4 the three main HEV related refinement issues of varying levels of ICE masking, varying control strategies and inclusion of interior synthesized sounds are discussed. This leads onto method and assessment selection for these three areas and a review of the assessments created and carried out. A recommended process for further related work was constructed and also discussed in this section.

The main achievements of this project are discussed in chapter 5. A review of the newly created HEV sound quality assessment model is discussed in conjunction with a recommended process to follow as an aid for new practice and further related studies. Finally within this section the benefits to the industrial partners involved are highlighted.

Recommendations for further research are discussed in chapter 6 and the report finishes off in chapter 7 with a conclusion highlighting the key innovations and learning from the research undertaken.

1.3 Portfolio Structure

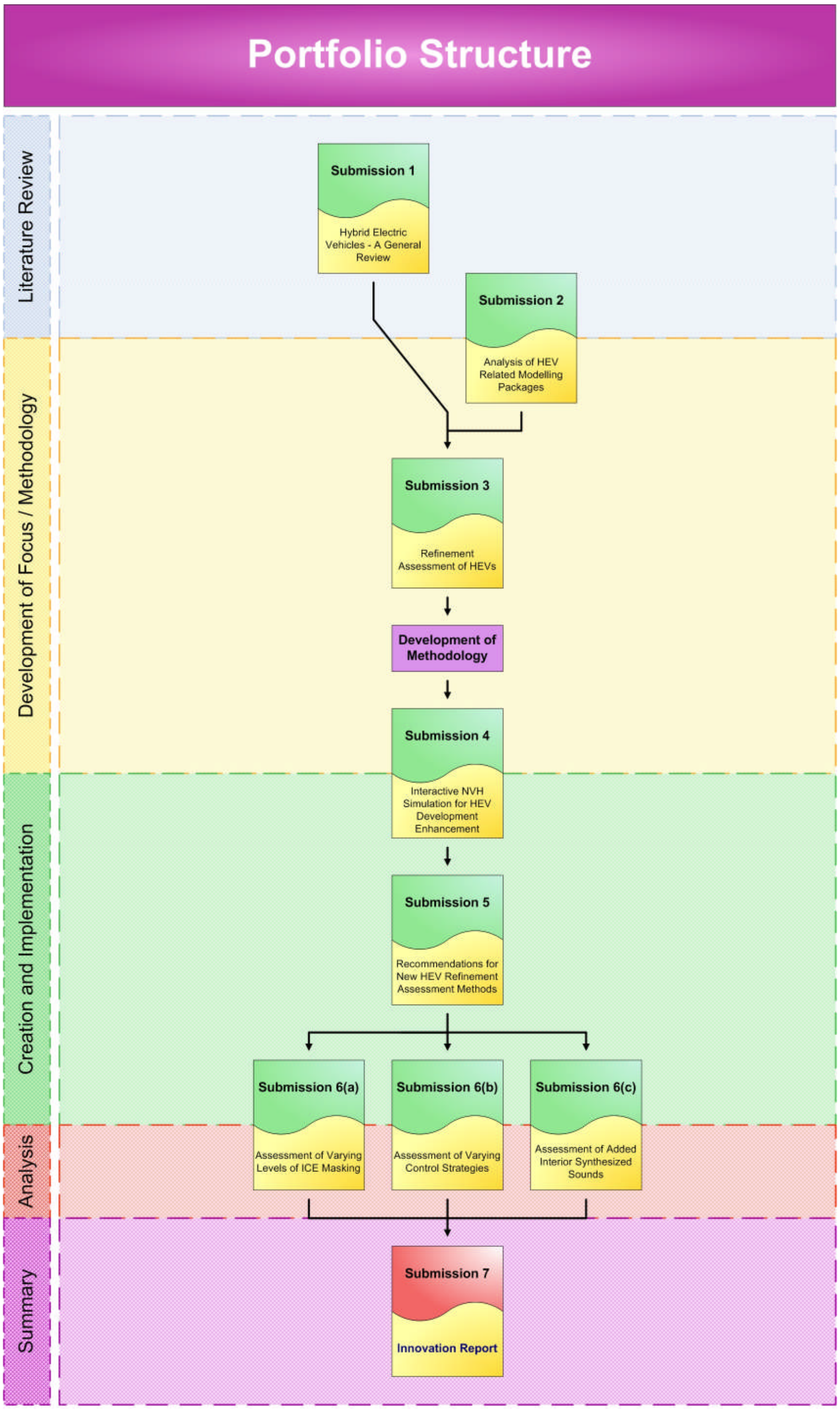

Figure 1.1 Portfolio Structure

The structure of the portfolio as shown in figure 1.1 is made up from 8 individual submissions numbered 1, 2, 3, 4, 5, 6(a), 6(b) and 6(c). The submissions themselves cover the full story of the project over the following stages.

- Literature Review of HEV Technologies, Motivations and Potentials
- Development of Focus / Methodology for Refinement Assessment of HEVs
- Creation and Implementation of a HEV model for interactive NVH simulation
- Analysis of new methods for assessing HEV refinement
- Summary of Learning and Recommendations

The route shown is the order in which the submissions flow in terms of the story and also the recommended order of reading. Each submission is now briefly reviewed in terms of its aim and how it links to other submissions.

- **Submission 1 – Hybrid Electric Vehicles - A General Review**

This report gives a general overview of hybrid electric vehicles (HEVs), focusing on the push for this technology, specific HEV operations and the market status at the beginning of the research. This initial review began to identify potential areas for development in order to accelerate the development of HEV technologies.

- **Submission 2 – Analysis of HEV Related Modelling Packages**

The reason for carrying out the work documented in Submission 2 was to establish a focus for the project. This report focused on the capabilities of a selection of HEV related modelling packages used by researchers, automotive manufacturers, suppliers and governments to model various hybrid powertrains to measure vehicle performance, emissions and fuel economy. This work not only reviewed the capabilities of these packages but also identified a number of potential areas where improvements could be made to improve HEV development. An area which was deemed to have high potential was that of customer assessment of HEV sound quality. Previously the objective measures of HEV design were well covered and/or being focused on by other research groups but very little effort was being made on the subjective assessment of such technologies. The work documented in this report, along with the findings from the initial literature review, led onto Submission 3; focused more towards the specific aims of the project and developing a suitable methodology to achieve them.

- **Submission 3 – Refinement Assessment of HEVs**

The work documented in this report initially focused upon the key areas (*business drivers*, *objective measures* and *subjective appraisal*) of any vehicle development process and how well each was covered within HEV design; highlighting a weakness in the *subjective appraisal* of HEVs. In Submission 2 sound quality assessment was highlighted as a gap and was chosen as the focus for this research.

A more specific review of the literature was carried out to establish specific HEV refinement issues in addition to those of conventional vehicles. The literature reviewed was within three key areas: academic literature; HEV car reviews and online blog feedback. The key areas where the specific HEV issues were identified and grouped were: reduced masking, interference between new sources, low sound of interior during idle and exterior sound. The application of an interactive NVH simulator was chosen to develop solutions to these issues as it allowed for the development of customer assessments within a suitable context and modelling environment.

- **Submission 4 – Interactive NVH Simulation for HEV Design Enhancement**

This report covers the work carried out to develop a methodology for capturing the sound, vibration and component data from a HEV, turning the data into a suitable vehicle model and installing it into an interactive NVH simulation environment to be used for new HEV focused customer assessments. A process was created and validated using a *Toyota Prius* as a case study. Once completed the HEV specific refinement issues were revisited and three areas were chosen for the specific development.

- **Submission 5 – Recommendations for New HEV Refinement Assessment Methods**

The specific HEV refinement issues selected were: varying levels of ICE masking, varying initial control strategies and added interior synthesized sounds. A brief review of the conventional sound quality assessment process was carried out, which led onto the recommendation for necessary modifications to cater for new HEV specific requirements. Recommendations were made for each HEV refinement issue chosen. This included the selection of suitable jury evaluation techniques (e.g. paired comparison), vehicle stimuli (so participants can compare suitable selections) and drive cycle selections (representative of HEV operation and usage).

- **Submissions 6(a, b & c) – Assessment of Varying Levels of ICE Masking, Varying Control Strategies & Added Interior Synthesized Sounds**

These reports document the work carried out to develop new methods to assess the impact varying levels of ICE masking, varying initial control strategies and added interior synthesized sounds in HEVs had on customer preference, through interactive subjective assessment. The results from the assessments were also analysed and reviewed. The learning and key steps from the assessments were identified, with process flowcharts being produced as a stand alone tool for recommending to NVH engineers how they would carry out further similar related assessments. The outputs from this work led onto the recommendation for new practice for assessing specific HEV refinement issues. This is presented in the form of process flowcharts.

2 The Need to Improve HEV Sound Quality Assessment

This section explains the choice of HEV sound quality assessment as the focus for the project. Initially a recommended list of areas of specific interest in HEV development was compiled through a literature survey. A review of current practice was then conducted to determine any gaps during HEV development through assessing a number of HEV related modelling packages against this list. The assessment of HEV refinement was found not to be covered in any significant depth prior to this work and issues being raised through early research and customer reviews began to emphasise that improvements were required. The aim of the project was decided and the application of interactive NVH simulation was chosen as a suitable approach for introducing new methods for HEV sound quality assessment.

2.1 Reviewing Current Practice

To review the objective nature and potentials for subjective improvements of HEV development a study of HEV related modelling packages was carried out in conjunction with the key areas of HEV development defined during the literature review.

2.1.1 Defining the Key Areas of HEV Development

Leading on from the initial literature review it was possible to breakdown HEV drivers for development into three key areas: *business drivers, objective measures* and *subjective appraisal*. Prior to the study of HEV related modelling packages it was considered that the subjective assessment of HEVs was treated poorly; which led to an initial review of the literature for HEV development considerations.

The *business drivers* segment covers areas such as: cost benefit analysis, future HEV sales estimations and business support tools; which all have an impact on the decision making process when wanting to design, produce or purchase a HEV. A snapshot of the current work at that time within this area included: evaluation of a low cost series hybrid vehicle through simulation within *ADVISOR* (Doerffel and Abu-Sharkh, 2002), with only performance related criteria being assessed with little consideration for subjective issues. Other work focused on retail and lifecycle cost analysis of a HEV through objective simulation through *ADVISOR* (Lipman and Delucchi, 2006), which included a full breakdown of individual component costs (maintenance, replacements and disposal), yet little consideration for the impact driving style might have had on the life of components. Work was also carried out on lifecycle and fuel economy analysis of a fuel-cell hybrid vehicle through the creation of system and control block models based upon physical attributes (Seong, Kwi and Soo Oh, 2002), yet there was no consideration for specific driver use and preference for a particular vehicle model. Another example of previous work included the development of a cost benefit analysis support tool focused upon the full envelope of lifecycle costs of a HEV to the customer (Breddy, et al, 2007). This tool is linked into the HEV modelling package *WARPSTAR* (Walker, et al, 2006) to predict the objective performance of current and potential HEV designs; enabling the accurate forecast of real world fuel consumption.

The *subjective appraisal* of HEVs had very little literature in terms of work focus but a lot of issues were beginning to be raised both through initial research attempts and through customer opinions; supporting the need to improve the refinement assessment of

HEVs. A strong consideration for the assessment of vehicle refinement is now expected by consumers of all modern day vehicles. Refinement has become one of the key engineering design attributes to be addressed during the development of new vehicle models. The assessment of refinement falls into the wider area of NVH, and one of the key focuses of NVH development, particularly over the last 30 years has been to develop quieter and more comfortable vehicles. Yet it has been suggested that some modern vehicles have become too quiet; lacking in character and quality as a result (Bunting, 2002). In addition to the conventional NVH issues, there has been little to no work on HEVs.

HEV development covers many areas including: cost analysis, performance prediction and business support. Prior to this research a lot of effort had been made with the transition from conventional ICE vehicles to HEV technologies with objectively focused measures (as documented from the review of literature shown in this chapter) yet very little evolution with the subjective assessment of HEVs.

2.1.2 Study of HEV Related Modelling Packages

One of the key aims of the study of HEV related modelling packages carried out was to identify any gaps. Based upon a review of literature focused on HEV development a selection of vehicle areas which should be considered of particular importance during early HEV development was created. The full list of areas chosen and selection of the most common and most used HEV related modelling packages assessed via *Pugh Matrix* analysis included: vehicle purpose (e.g. type of service and maximum speed/acceleration requirements); vehicle dynamics (e.g. torque and power requirements) and battery information (e.g. technology choice and *state of charge* [SoC] levels) which can be seen in full within appendix 9.1. The most appropriate package/s were selected for each individual area and *ADVISOR* (Wipke, Cuddy and Burch, 1999) was deemed the most suitable HEV related modelling package as a general user platform.

Through identifying the gaps (as shown in appendix 9.2) in using such packages it was possible to select the focus for the project. As shown in figure 2.1, *sound quality assessment* is just one area within *subjective appraisal* which was highlighted as requiring further research advancement through the results from the *Pugh Matrix* analysis.

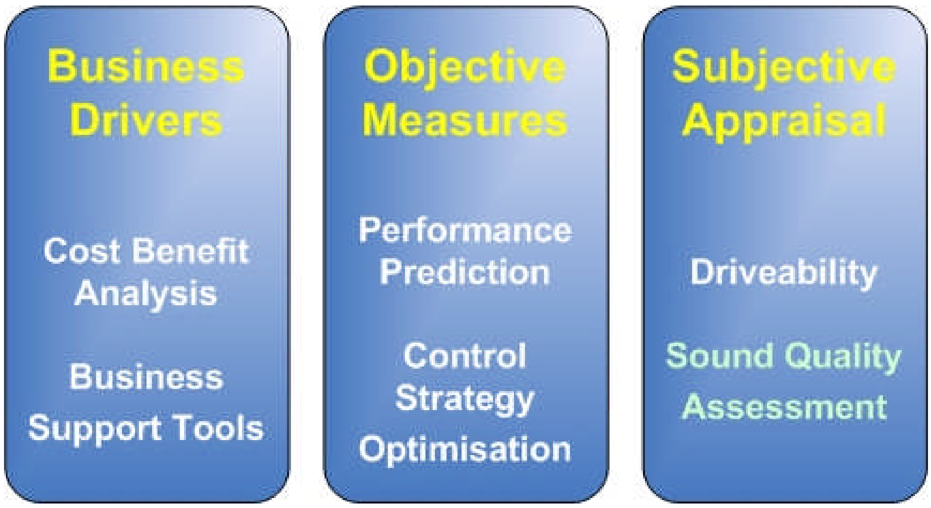

Figure 2.1 Key Areas of HEV Development

Business drivers and *objective measures* were the two areas which were most established and had more focus on in terms of research and development to date; which is backed up by results of the assessment of HEV related modelling packages. The area of *subjective appraisal* is the strand which was highlighted both within the literature and supported by the review of HEV related modelling packages as not being particularly well covered, yet still very important.

2.1.3 The Potential for HEV Subjective Appraisal Improvement

Sound quality has become an ever increasing part of the vehicle development process. Not only is the level important, quality of the noise is the thing which can attract or put off potential customers. Traditional objective approaches including FFT analysis can tell you a lot about a particular vehicle sound but only through customer jury evaluation can a design engineer find out whether the potential sound is appealing or not. Focusing on sound quality assessment as a whole, previous work has included the development of a standard process for assessing automotive sounds (Otto, Amman, Eaton and Lake, 2001), taking into consideration: how a listening room should be set up; number and variety of participants for specific tests; test preparation and delivery; evaluation methods; and analysis methods. Leading on from these recommendations for best practice, work has progressed into understanding how customers are actually making their decisions during assessments (Fry, Jennings, Williams and Dunne, 2004), improving the context in which customers are performing these assessments; moving from the traditional on-road and listening room approaches towards interactive assessment within an NVH simulator (Allman-Ward, Williams, Dunne and Jennings, 2004).

The introduction of HEV technologies however has introduced new specific issues that have not previously been considered or apparent within conventional *internal combustion engine* (ICE) vehicle development. It is clear that HEVs present new refinement challenges at a time when most conventional vehicle NVH issues are understood and can be controlled.

2.1.4 HEV Refinement

Evidence on the current practice for HEV refinement was broken down into three key areas: *academic literature*; *HEV car reviews* and *online blog feedback*.

An early piece of work was carried out on the first *Toyota Prius* (Yoshioka and Sugita, 2001); which began to identify refinement problems with the HEV, making recommendations for the introduction of new technology developments to noise and vibration reduction. One example from the study showed that at low ICE speeds the *Toyota Hybrid System* (THS) allows for high torque operation resulting in better fuel consumption; yet this tended to result in a body vibration and drone noise due to fluctuations in the ICE torque during constant speed and slight acceleration loadings. This was a new NVH issue purely related to the HEV configuration. This work was beginning to show that the conventional sound and vibration capturing process was not suitable for obtaining new specific HEV information and needed to be modified in order to capture the right amount of useful information from a HEV (Volinski, 2001). It was therefore considered that HEVs require a unique set of test conditions, dynamometer control, instrumentation and analysis. Issues began to be raised with the unsuitability of *wide open throttle* (WOT) as a suitable test condition for HEVs; a standard approach for conventional vehicle sound quality assessment (whether WOT's are even suitable for conventional vehicle assessment is another question). This work highlighted that one of the key NVH concerns with the HEV used was the starting and shutting off of the ICE whilst the vehicle was in motion; creating a torsional input to the system due to changes in combustion processing. This work suggested the need for improvements without giving details of what they should be. A later piece of work began to focus upon the new *sound quality* issues of HEVs (Franco-Jorge, 2002). Some of these were new specific issues and some were more evident in HEVs than conventional architectures. A list of the issues identified included: lack of interior idle noise (ICE off), high pitch whining when braking, constant ICE noise levels when accelerating and external noises being more apparent (road and tyre) due to lower levels of ICE masking. The most relevant NVH issue of electric motors identified in this research was when operating as a generator during *regenerative braking*, where there was an increasing sound as vehicle speed decreased. During these braking operations the tyre resonance and the braking noise of the motor were the most evident sound sources. These issues offer new challenges at a time when most traditional powertrain NVH issues are understood. Another piece of work focused the new refinement issues of HEVs and followed the release of the *Toyota Prius MKII* in 2003 (Vecchio and Van der Auweraer, 2003). This piece of work identified such issues as: ICE order tracking in presence of multiple rotating speeds. This work began to suggest that the conventional sound and vibration capturing process needed modification to cater for the specific needs of HEVs. This piece of work suggested that it would be beneficial to assess the correlation between the driver's actions and the interior noise of an HEV in order to understand and cater for their needs better.

A number of car reviews analysed gave rise to a number of new issues concerned with HEV refinement. A test drive carried out (August 2006) on the *Lexus GS450h* highlighted a number of issues regarding the refinement quality of the vehicle (Aucock, 2006). One issue highlighted was the excellent refinement of the drivetrain; however there were concerns that at low speeds the vehicle was unsafe when considering pedestrian safety. The roar of the tyres was also more evident; ruining the refined image *Lexus* is renowned for. Another car review of the *Lexus RX 400h* mentioned that even though the acceleration was impressive (0 to 60mph in 7.5 seconds) it did not feel like the vehicle was going that quickly due to the low levels of overall sound (Kaehler, 2005). Another review of the *Lexus RX 400h* mentioned that there was a focus on improving the NVH characteristics of the vehicle with speeds up to around 40 mph being particularly quiet due to primarily electric only operation until the period where the ICE eventually started rotating and assisting in driving the vehicle. As an alternative the inclusion of a planetary gear transaxle would mimic a more conventional CVT transmission, which could result in better NVH characteristics. A quote from another source stated: "When you stop at the lights, it cuts the engine completely and you sit in perfect silence. So, inevitably, I nodded off. The only thing that woke me half-an-hour later was snoring – coming from the driver." (Hammond, 2005). There are two potential actions from such comments; one is that sound levels could be increased within the interior of HEVs to strengthen their similarities to conventional vehicles (for example through added interior synthesized sounds), or there must be more of an effort to try and change the current culture of drivers, tailoring them to accept the changing sound of eco-friendly vehicle technologies compared to conventional alternatives.

A final interactive review was carried out in which the author introduced new topics and commented upon existing topics on a selection of online blogs/forums focused on issues relating to HEV refinement. This led to a number of interesting responses which included: the brake sound being too hard and squeaky during *regenerative braking* (deemed not aggressive enough); a distinct whine from the electric motor when braking normally or moderately; and the need to include an indicator to show the transition between mechanical and *regenerative braking* aiming to achieve maximum energy recovery and understanding of the sound profile at any given time.

In conclusion there was very little literature documenting any significant work on modifying conventional refinement assessment techniques for specific HEV issues; with a clear need to improve conventional methods as expressed by the opinions and understanding gained from the literature. This strengthened the need to improve the refinement assessment of HEVs; identified as a gap from the initial study of HEV related modelling packages. Other work had been carried out and is reviewed in greater detail within Submission 3.

2.2 HEV Sound Quality Issues

The new HEV specifically related sound quality issues reviewed were broken down into the following four key areas: reduced masking from the ICE; new HEV specific sources; information from sound and exterior sound of HEVs. The key issues within each of these four areas are given as follows:

- Reduced masking from the ICE

Within conventional vehicle architectures the ICE is the key sound source within the vehicle. The ICE in a HEV compared to a conventional equivalent is often downsized due to the additional power and torque offered by the electric motor, resulting in lower ICE masking as a result. Unwanted noises (e.g. wind and ancillary) that the ICE masks successfully in many conventional vehicles have become more evident within HEVs. Research has also highlighted that tyre noise is more dominant in HEVs compared to a conventional ICE equivalent (Vecchio and Van der Auweraer, 2003). Therefore, a reduction in ICE sound does not always lead to a more refined vehicle. Standard component sounds are more noticeable and there are new specific HEV sound sources to consider too, including electric motor whine and electronic switching.

- New HEV specific sources

Not only is there the addition of sound and vibration from new HEV components, there is also additional structure-borne noise due to HEVs having more complex powertrains including series, parallel and other alternatives. Previous work has highlighted that during the event of *regenerative braking* there are occasions when the braking can create high pitch whining (Franco-Jorge, 2002). Sounds such as these can influence driving styles (positively or negatively) and change driveability. There are also high frequency noises due to boost converter systems, inverter interaction and harmonic issues with the ICE interfering with orders of the electric motor at resonant frequency bands (Vecchio and Van der Auweraer, 2003). Increases in M/G speed/noise in HEVs can occur during regenerative braking as the vehicle’s speed decreases. This can be disconcerting and could influence customer perception, comfort and driving style. Previous research has focused on the development of an energy management strategy for a parallel HEV to optimise driveability (Cacciatori, Vaughan and Marco, 2006) – it is possible that a similar approach would be appropriate for sound quality.

- Information from sound

Sound level reductions due to hybridisation can change customers’ perceptions of the brand quality of a particular automotive company/vehicle. However there are also a number of related issues for HEVs around other information conveyed to the driver. For example during idle, when the ICE can be off (unless the battery SoC is significantly low), some drivers question whether the vehicle is even switched on at all.

One way to increase sound levels and influence the perception of sound within HEVs could be through the introduction of synthesized sounds within the interior. Such options would also need to take into account the effect this would have on performance due to changes in driver behaviour. Many drivers act based upon the sound they experience, for example their gear change strategy can be influenced by feedback from engine note.

- Exterior sound of HEVs

Pedestrian safety is another issue for HEVs, especially when they operate in electric-only mode within a city. A pedestrian may not be able to hear a HEV approaching. Therefore suitable artificial audio stimuli may need to be considered in order to improve pedestrian safety. Not only are the safety factors concerned with exterior sound important for HEVs, but also the influence it has on brand quality. A bland or annoying sound from a HEV could also have a negative effect on a customer's perception of a particular vehicle or brand.

2.3 Project Aim

With a number of new HEV related refinement issues identified, the aim of the project was chosen:

"To develop the new methods necessary for assessing sound quality during the HEV design process in order to aid early engineering decisions (and improve overall vehicle desirability and reduce customer acceptance problems)."

In order to encompass the additional and more complex issues surrounding HEV refinement through sound quality assessment it became clear that new methods needed to be developed which took these HEV specific matters into account. The specific objectives of the work were:

- Review
  - Classification of new HEV sound quality issues
  - Approaches for carrying out HEV sound quality assessment
- Develop
  - New methods for assessing HEV sound quality
- Test & Capture
  - Trial of methods through real world case study (e.g. current market HEV)
- Validate
  - Tackle a selection of identified HEV sound quality issues through subjective assessment
- Implement
  - Provide a framework to aid further HEV sound quality studies

2.4 Interactive NVH Simulation

Given these new challenges for the sound quality of HEVs, the best approach for learning about perceptions needed to be determined. Two key requirements were chosen based upon recommendations of previous sound quality assessment for conventional vehicles (Jennings, et al, 2007); these were:

- To be able to assess the sound from vehicle models of both current and future vehicle designs. To make comparisons between HEVs and comparative conventional ICE vehicles easily and to trial new HEV selections.
- To be able to assess those sounds in real-time, with the option of both fixed and free drive scenarios, and within an appropriate context. Providing a suitable real-world context in order for such assessments to be suitable.

Three potential approaches were reviewed: HEV modelling software add-on; *Matlab/Simulink* development; and interactive NVH simulation. There were potentials of creating add-ons to a number of the HEV related modelling packages reviewed at the beginning of the project. In terms of fulfilling the key requirements, it is possible to create HEV models within a number of these packages, with the ability to assess both current and future vehicle designs (as long as component data was available). However, all of the current modelling packages reviewed do not allow for the playback of sound, and it was uncertain whether it would be possible or worthwhile creating an add-on for an existing package to accommodate for this. Although a number of these modelling packages fulfilled the objectively focused needs of HEV design, they were not suitable for the developing and learning more about sound quality of HEVs. The potential of creating a model within *Matlab/Simulink* was another possibility; but similarly to add-ons to existing HEV modelling software packages there were concerns about the fulfilment of a suitable real-world context. Interactive NVH simulation provides customers, engineers and key decision makers the ability to create and test current and future vehicle designs, aid and improve potential designs and offer this within a suitable real-world context. The only approach to satisfy both requirements is interactive NVH simulation. However, for specific HEV needs the only key requirement which was uncertain for this approach, was the ability to create a suitable HEV model and then implement this into an interactive NVH simulation framework. Even though there was uncertainty of being able to create a suitable HEV model, it was clear that it was the most suitable approach based upon the fulfillment of the other key requirements.

Through the capture of sound, vibration and objective data from a vehicle under a structured set of test conditions it is possible to use this data to create a vehicle model for interactive NVH simulation (Williams, et al, 2005; Williams, Allman-Ward and Bernard, 2006). As shown in figure 2.2, a vehicle sound is built up from a number of individual components including: ICE, wind, road and tyre noise.

For this project, the *B&K PULSE NVH Vehicle Simulator*, an interactive NVH simulation framework which can be used in both fixed-base vehicle and interactive desktop setups (see figure 2.3) was used. The simulator has the capability of being able to implement and build a selection of vehicle models (component level up) for interactive assessment by either experts (engineers) or non-experts (customers). Assessments themselves can be created and analysed within the supporting software. A standard selection of jury evaluation methods is available for running studies, including semantic pair evaluations and paired comparisons. The simulator has previously and is currently being used for conventional vehicle design projects and much work has gone into creating new methods and analysis techniques for the assessment of conventional ICE vehicles (Jennings, et al, 2007).

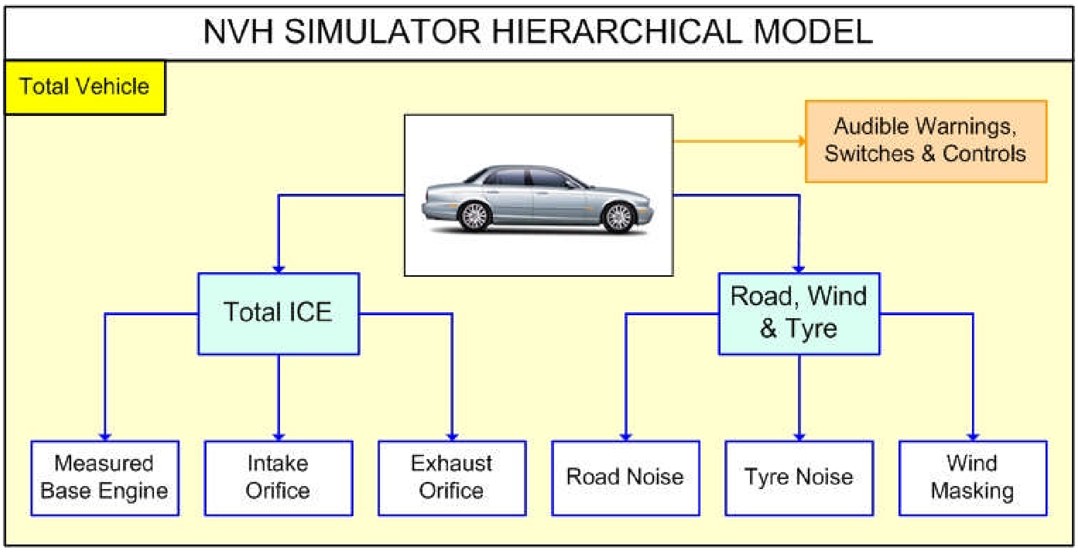

Figure 2.2 NVH Simulator Hierarchical Model

Interactive NVH simulation offers engineers and customers a suitable real-world context with the ability to assess a number of current and future vehicle designs in a structured manner, which listening room and on-road assessments cannot offer. Listening room based assessments offer the ability to make quick and accurate assessments of both current and future vehicle designs but a key problem is the lack of a realistic interactive context. With on-road assessments a realistic real world context is easily achieved, but drawbacks include the time taken to switch between vehicles (poor back to back comparison), lack of experimental control and the inability to assess future vehicle designs. Interactive simulation offers the benefits of both methods, but has none of the drawbacks. It has the capability to play and switch between selections of vehicles at the touch of a button, playing the correct sound through a set of headphones.

Interactive NVH simulation therefore potentially provided an ideal environment for further learning about new HEV-specific sound quality issues. It was therefore necessary to learn how to create a model of a HEV suitable for use within an interactive simulation framework.

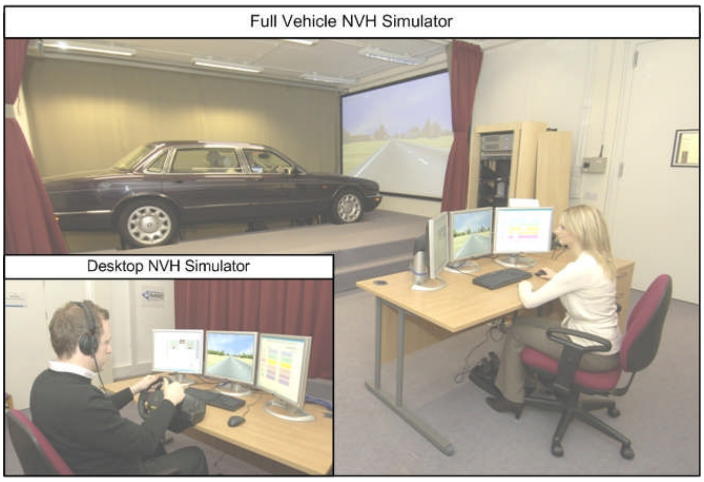

Figure 2.3 Interactive NVH Vehicle Simulator (Desktop and Full Versions)

3 Research Methodology

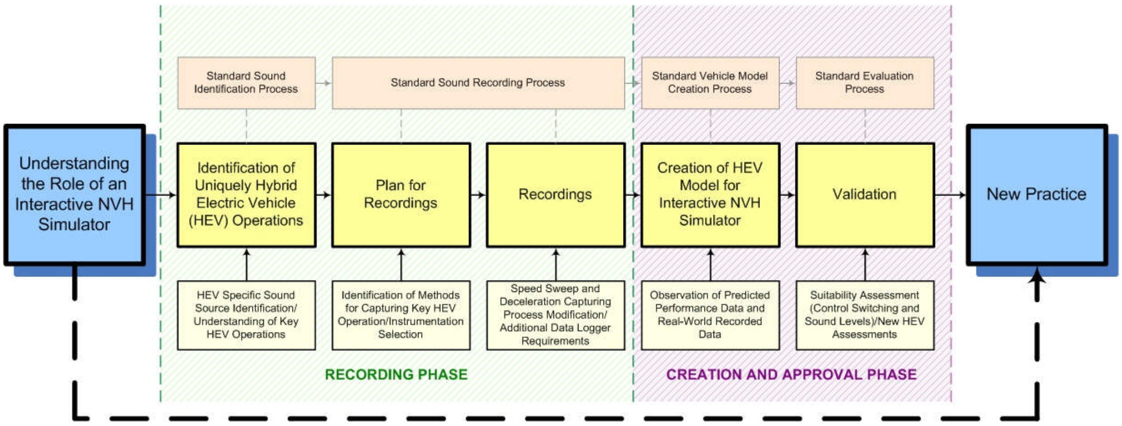

Figure 3.1 HEV Refinement Assessment Process

Figure 3.1 shows the identified steps; from understanding the role of interactive NVH simulation through to the creation of new specific HEV refinement related sound quality assessments as a validation tool for assessing the HEV model created. As highlighted in orange the top level process taken for conventional vehicle sound and vibration recording, vehicle model creation and implementation is shown. This basic structure was reviewed as documented in Submission 4 and used as a reference for the development of new methods for the sound and vibration recording, vehicle model development and usage for refinement related sound quality assessments of HEVs (as discussed in the following section).

The key areas where specific improvements and entirely new areas (e.g. creation of a HEV model) needed to take place were broken down into the following sections: *Identification of Uniquely HEV Operations, Plan for Recordings, Recordings, Creation* *of HEV Model for Interactive NVH Simulation* and *Validation* (shown in yellow in figure 3.1).

Sound and vibration recording of conventional ICE vehicles is normally carried out on a test track in order to ensure high levels of repeatability. Part of this process involves the use of standard speed sweeps of the vehicle. During this test procedure a vehicle is taken through a number of constant acceleration runs (e.g. 0%, 20%, 40%, 60%, 80% and 100% throttle pedal loadings) and the relevant sound and vibration related information is recorded. However, simple test runs such as these would not capture sufficient data from HEVs due to the more complex nature of the vehicle operation and additional components. With the case of most HEVs (similarly to many ICE vehicles) throttle position is controlled by *drive-by-wire* and is not directly related to pedal position; hence the respective control strategy ensures that suitable component operation for any given power/torque demand. So the percentages would relate to actual pedal position rather than throttle position.

There are clear differences between conventional ICE vehicles and HEVs. New HEV specific component architectures and more complex control strategy options compared to conventional ICE vehicles mean that such conventional processes would need to be modified to accommodate for these new specific needs. Additional steps required to tailor it towards HEV development needs were therefore considered.

The first step was to identify the key factors that would affect the sound of a HEV in conjunction with conventional vehicle components and to highlight the sound contributions which would need to be captured during the sound and vibration recording phase. Additional HEV components include: M/G and battery packs (as shown in green in figure 3.2).

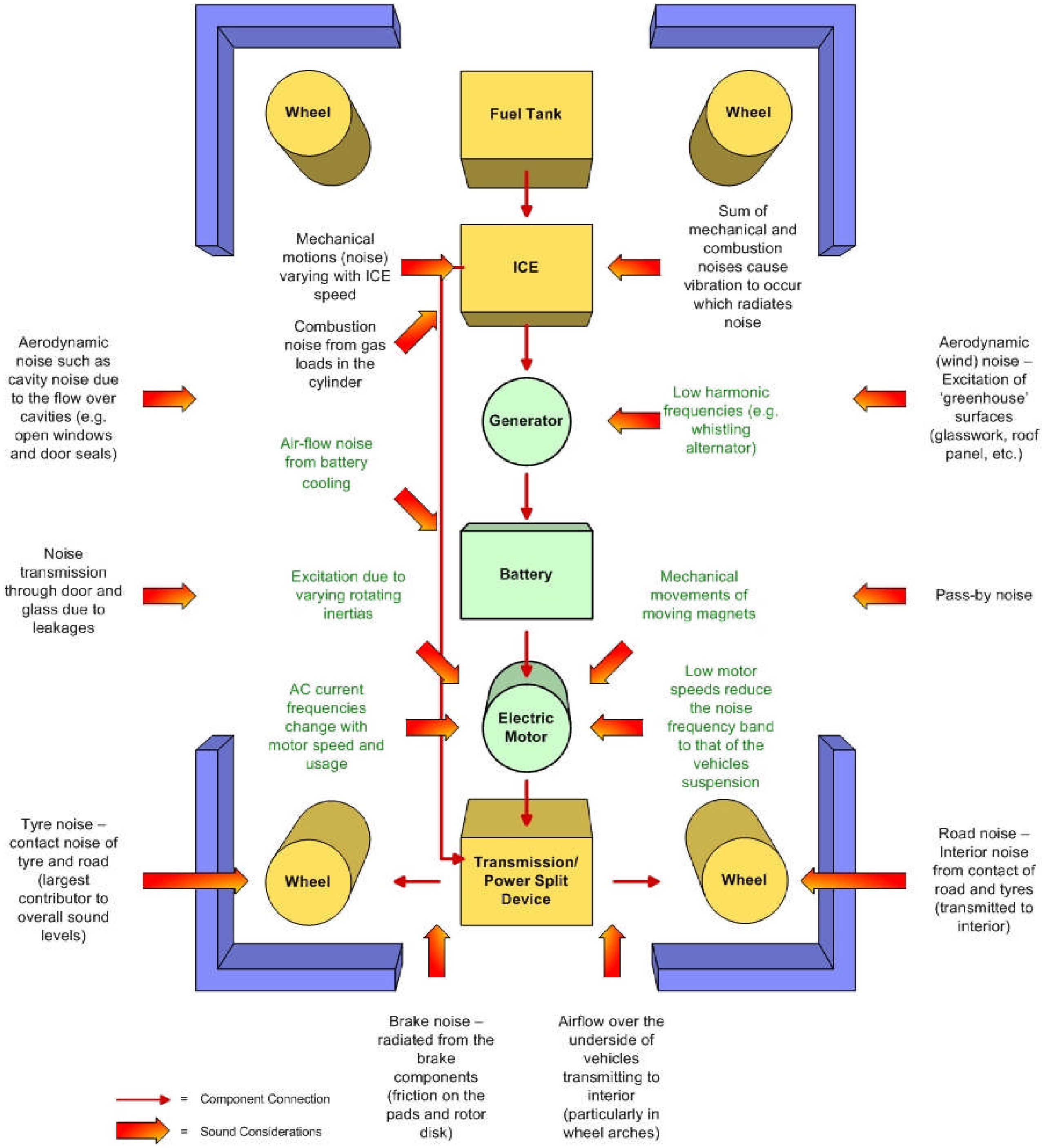

Figure 3.2 Key Factors that Affect the Perception of Sound within a HEV

As previously identified within the literature, the additional components and more complex operation of hybrid vehicles present new harmonic and excitation issues as illustrated in figure 3.2; which were not present or apparent for traditional ICE vehicles. Another example is the battery; which does not create any sound, yet the SoC of the battery can have a significant effect on the overall sound profile of the vehicle as the SoC is an input into the vehicle control strategy which, in turn, affects other operations such as the switching of components. So therefore, there was the requirement to capture not only sound and vibration data but also additional component data such as battery SoC.

In addition to identifying key factors that would affect the sound of a HEV, it was also important to assess the actual operation of HEVs. With HEVs having a complex control strategy and additional features such as regenerative braking, it was crucial that the sound and vibration recording process took these issues into account; ensuring that the appropriate levels of information were captured. The basic operation of a selection of HEV architectures (start/stop, series and parallel) have previously been covered within Submission 1; highlighting key HEV specific operations such as: regenerative braking, electric only and ICE off conditions at idle. Some key HEV operations are shown in figure 3.3.

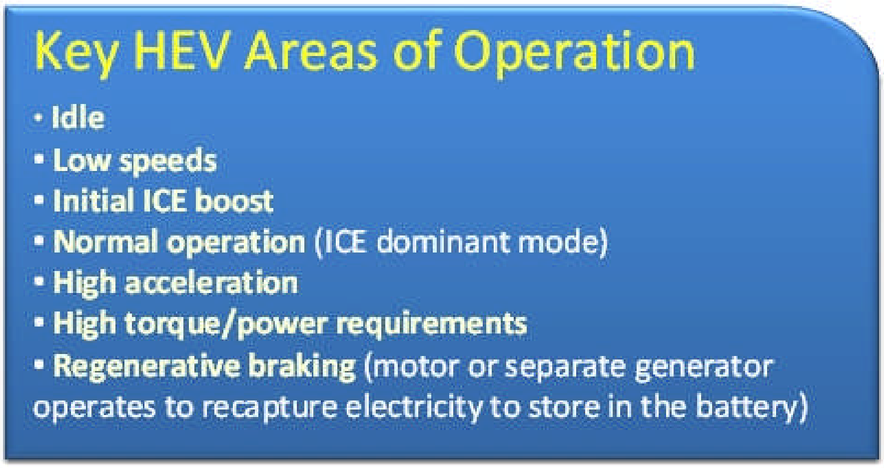

Figure 3.3 Key HEV Areas of Operation

These key areas can be expanded to define the specific regions of operation for any given HEV through the use of additional data such as vehicle nomographs and vehicle specification datasheets. A vehicle nomograph is a chart which shows the relationship between individual vehicular components and how their operation can affect other components. In the case of a HEV, the three key *auxiliary power units* (APUs) are the ICE, electric motor and generator (if installed as a separate component). The general case for a HEV is that these three components are all connected mechanically via a planetary gear set. The electric motor for example can be represented as a function of vehicle speed as its operation is directly proportional to wheel speed.

It was possible to put together a list of required instrumentation for both sound and separate data logging purposes prior to the sound and vibration recording process (as shown in figure 3.4).

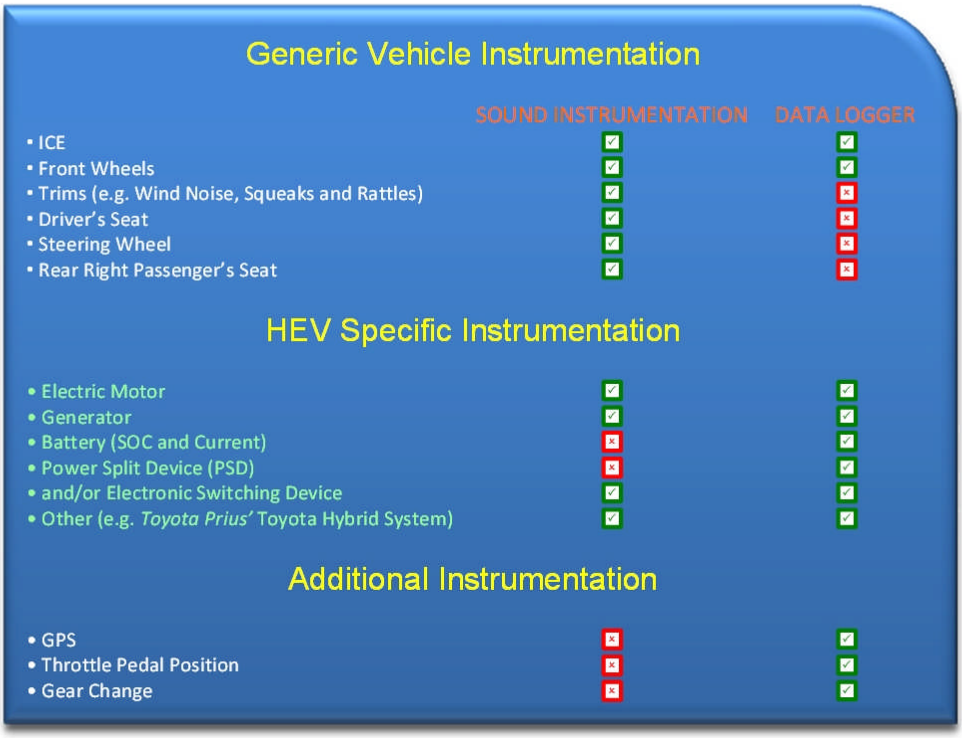

Figure 3.4 HEV Sound Recording Process Instrumentation

The conventional set of standard sweep test runs were expanded in order to ensure that sufficient information was captured for each of the key HEV operations identified. In order to achieve this, a representative drive cycle was created by combining the *New European Driving Cycle* (NEDC) (drive cycle for emission certification of light duty vehicles in Europe) and *Highway Fuel Economy Cycle* (HWFET) (developed by the US EPA and used for determining fuel economy of light duty vehicles on a chassis dynamometer) standard emissions drive cycles, which encompass key HEV operations (see figure 3.5). The reason for doing this is to improve the understanding of the component switching/operation during these periods for any given HEV.

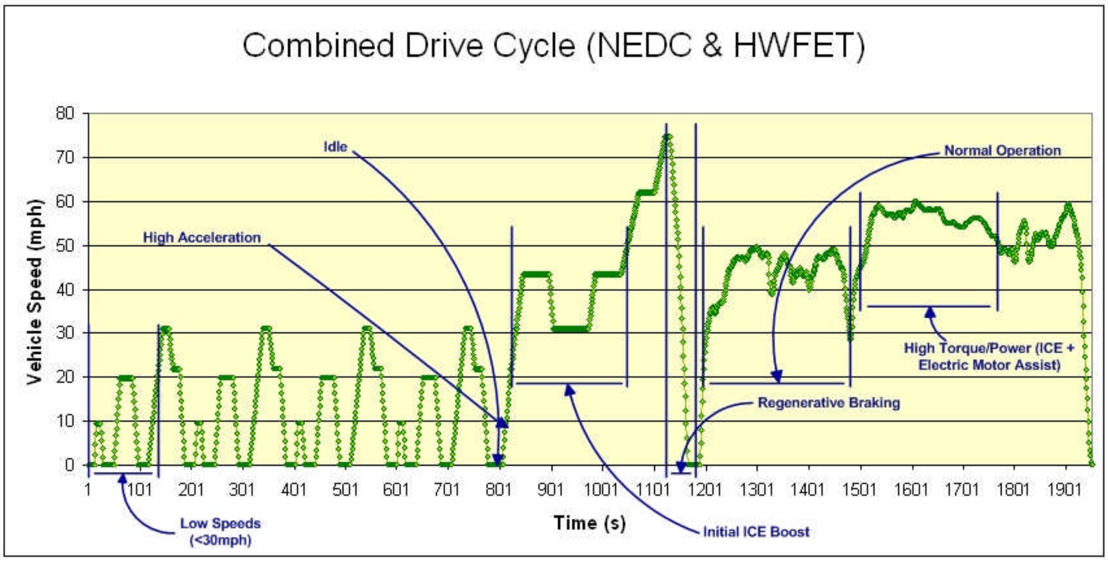

Figure 3.5 Representative HEV Drive Cycle

A HEV model could then be built up from conventional sound and vibration elements as previously shown in figure 2.2 (e.g. road, wind and tyre contribution) with the addition of new HEV specific factors. A HEV hierarchical model has information on electronic switching, electric motor and generator components as highlighted in figure 3.6.

The HEV model was created through a selection of lookup tables which produced the relevant sound in relation to the vehicle and component speed/torque profile at that time. Lookup tables were created for the ICE only, electric motor only and a combined one; in addition to the sound contributions (as shown in figure 3.6).

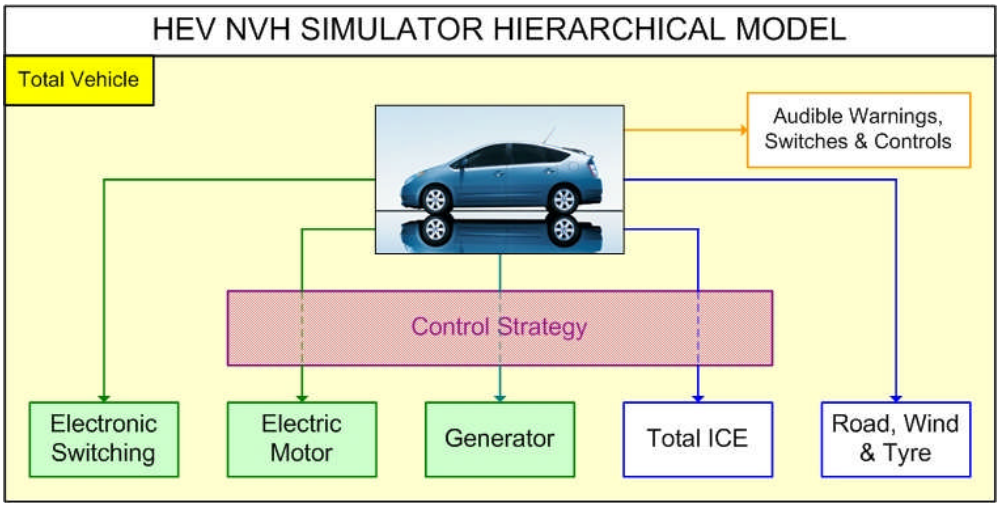

Figure 3.6 HEV NVH Simulator Hierarchical Model

The control strategy of the *Toyota Prius* was represented within the HEV model as the extended number of recordings carried out ensured sufficient information was captured at varying conditions (e.g. battery SoC level) to achieve this. Varying component operation could be represented easily by alternating which lookup table was being referred to at any given time in terms of the sound being produced. This could be representative of a real-world control strategy modification in terms of the resulting change in vehicle sound profile. More complex control strategy options were to be created externally through ADVISOR. To represent varying initial battery SoC within an assessment for example, a drive cycle was run first in ADVISOR. The relevant initial conditions/control strategy options were selected (e.g. EV only operation) and the resulting component and vehicle speeds fed back into the drive cycle file for the creation of stimuli for assessment. This results in a representative vehicle sound profile being produced.

4 A New Approach to HEV Sound Quality Assessment

It was important to validate the new approach as shown in figure 3.1 and discussed in the previous section to ensure that it was suitable for real world usage. In order to trial the new approach, a case study with a *Toyota Prius* was undertaken.

4.1 *Toyota Prius* Case Study

A *Toyota Prius* was chosen for the case study as it is one of the most common HEVs. The *Toyota Prius* was the world's first mass produced hybrid vehicle, introduced in Japan in 1997 (Crowley, 2004). The generic steps described in the previous section were modified for the purpose of the case study in order to determine the specific component operational limits and key HEV operations for a *Toyota Prius*, as shown in figure 4.1.

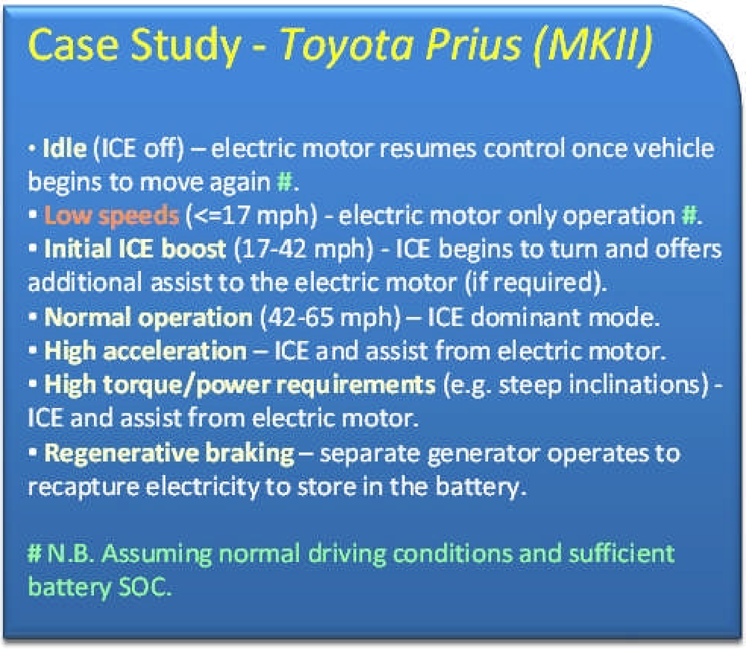

Figure 4.1 Key Areas of Operation for the *Toyota Prius*

The *Toyota Prius* nomograph shown in figure 4.2 is an adaptation of previous work carried out by the *Argonne National Laboratories* (Snyder, 2001), with measurements taken from the *Toyota Prius (MKI)* (available only in Japan at the time) and modified for the operation of the *Toyota Prius (MKII)*.

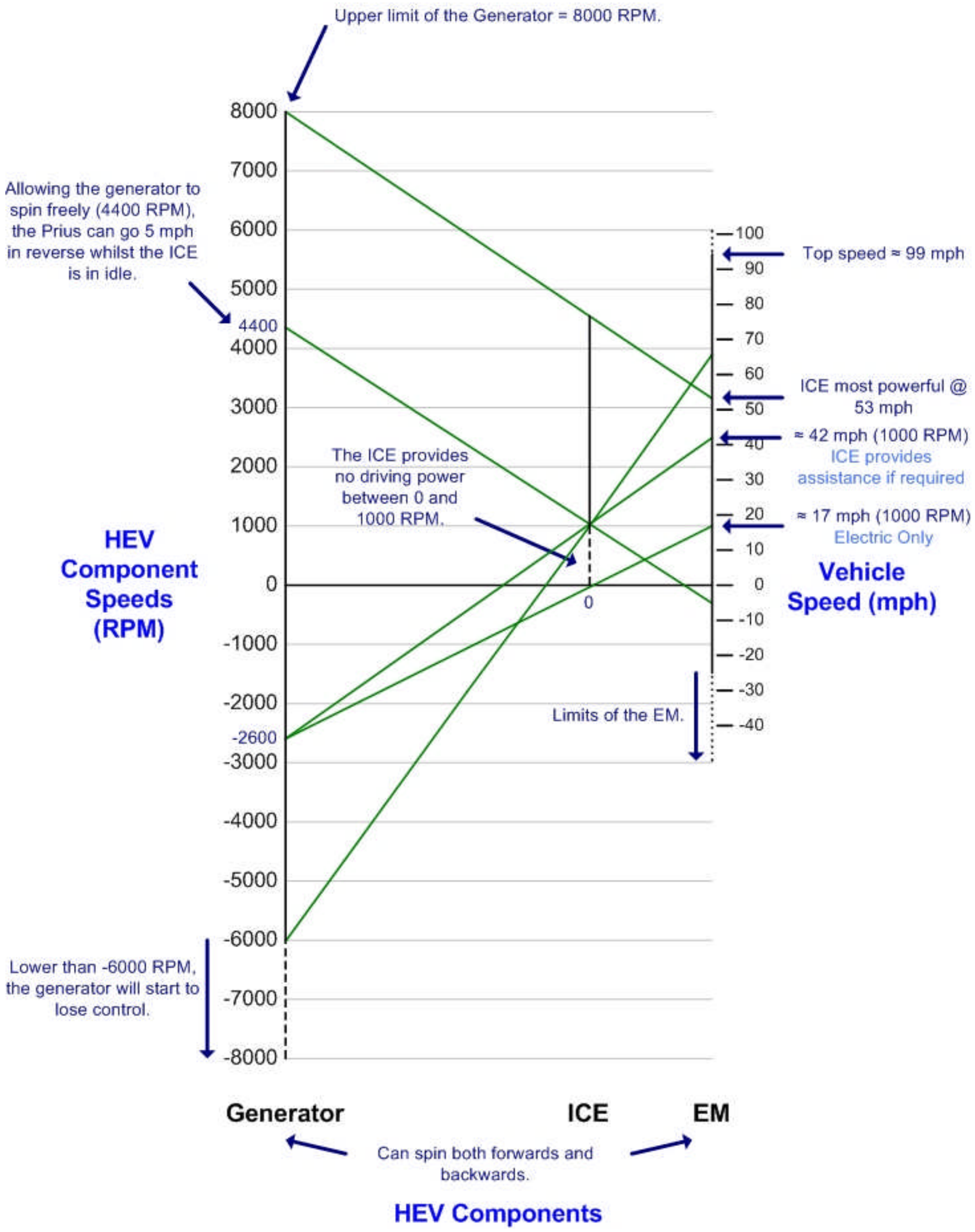

Figure 4.2 *Toyota Prius* Nomograph, adapted from Snyder (2001)

A vehicle nomograph is a graph consisting of individual component speed (e.g. ICE speed) scales. Each of the three components in the *Toyota Prius* are connected mechanically, therefore if two component speeds are known the third can be derived by connecting a straight line trough the two known component speeds. This was used to help determine the specific operational limits of a *Toyota Prius* as shown in figure 4.1.

A number of key points highlighted in figure 4.2 include:

- The electric motor (EM) operates as a function of wheel speed, hence lying on the same axis as the vehicle speed.
- The ICE begins turning at 17 mph (electric motor is rotating at 1,000 RPM). The ICE will cycle on and off as needed up to 42 mph; entering *normal operation* (ICE dominant mode) where the ICE will always turn, providing power to drive the vehicle due to the limits of the electric motor being reached.
- The ICE will continue to be the dominant APU under normal conditions up to 65 mph, beyond this the electric motor can provide additional power required for higher speed/torque demands.
- Maximum vehicle speed 99 mph. (with 100% throttle applied).

Once the key areas of HEV operation had been defined for the *Toyota Prius* case study the results were then used to create plots of ICE, electric motor, generator usage and full vehicle operation for varying vehicle speeds and battery SoC (also considering current torque demand level). It is important to understand the individual component operation, in addition to the effect on other component operations; especially when considering the information required for capture during the sound recording process. An example of the ICE usage for the *Toyota Prius* is shown in figure 4.3.

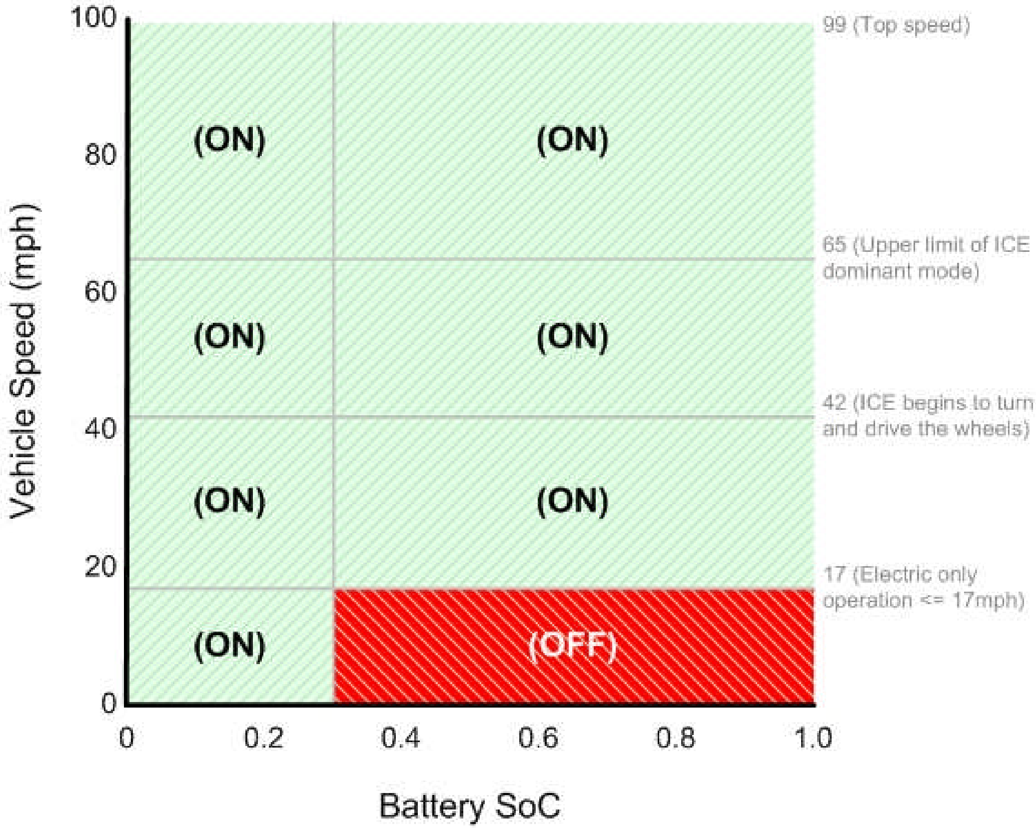

Figure 4.3 *Toyota Prius* ICE Usage

The region between 17 - 42 mph for example, is defined as the *Initial ICE boost* region. This is where the ICE begins to turn, providing power to drive the vehicle when the limits of EV only operation are met, due to high torque demands and/or low battery SoC. Within the region highlighted red (figure 4.3) the ICE will only assist in providing power to drive the vehicle when there is high torque demand; as sufficient levels of battery SoC allow for electric only operation under normal conditions.

Using the individual component operation plots it was possible to create the following plot (figure 4.4); showing the four key operating regions in co ordinance with figure 4.2. This was used as guidance material during the sound recording phase and later used to select a suitable drive cycle for the assessments which moved between the *motor only* and *motor + initial ICE assist* operational states.

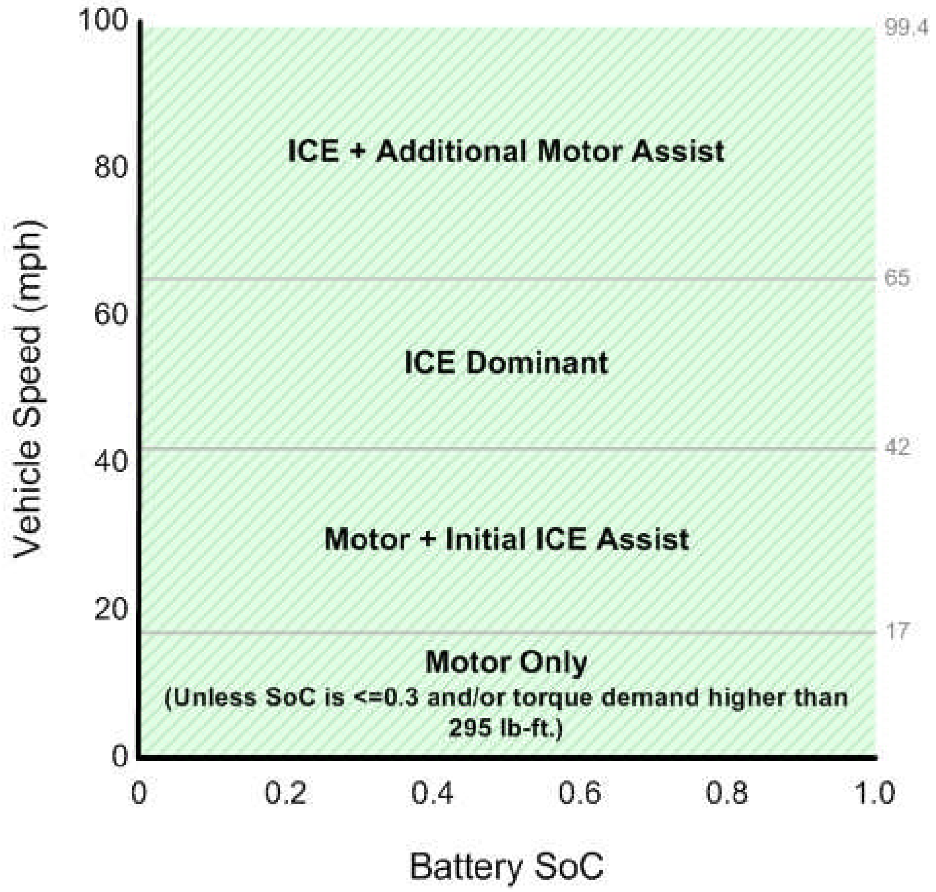

Figure 4.4 *Toyota Prius* Full Vehicle Operation

4.2 New HEV Sound Quality Experimentation

In order to gain further understanding of specific HEV related sound quality issues 3 experiments were designed and carried out. The objectives for these experiments were:

- To learn how to select driving conditions which are representative of HEV operation in which to assess HEV options during each of the chosen assessments.
- To find out whether changing the sound pressure level (dB) of the ICE in the same HEV configuration has an effect on customer perception.
- To see if varying HEV control strategy/initial conditions (e.g. initial battery SoC) can have a significant effect on the vehicle sound profile over the same driving condition.
- To see if participants can distinguish between a conventional ICE and a representative hybridised version of the same vehicle (with the addition of a sound component of an electric motor).
- To understand more about the opinions and decision making process of the participants.
- To capture the learning and recommendations in a form to aid the design of a more rigorous process.

Leading on from the four HEV sound quality issues previously identified (section 2.2), the process shown in figure 4.5 was carried out. Following on from the chosen objectives was the development of three experiments, with the learning from each experiment being used as an aid for the following experiment. The overall learning was used as a basis for recommendation for future HEV sound quality assessments through the creation of a set of process flowcharts.

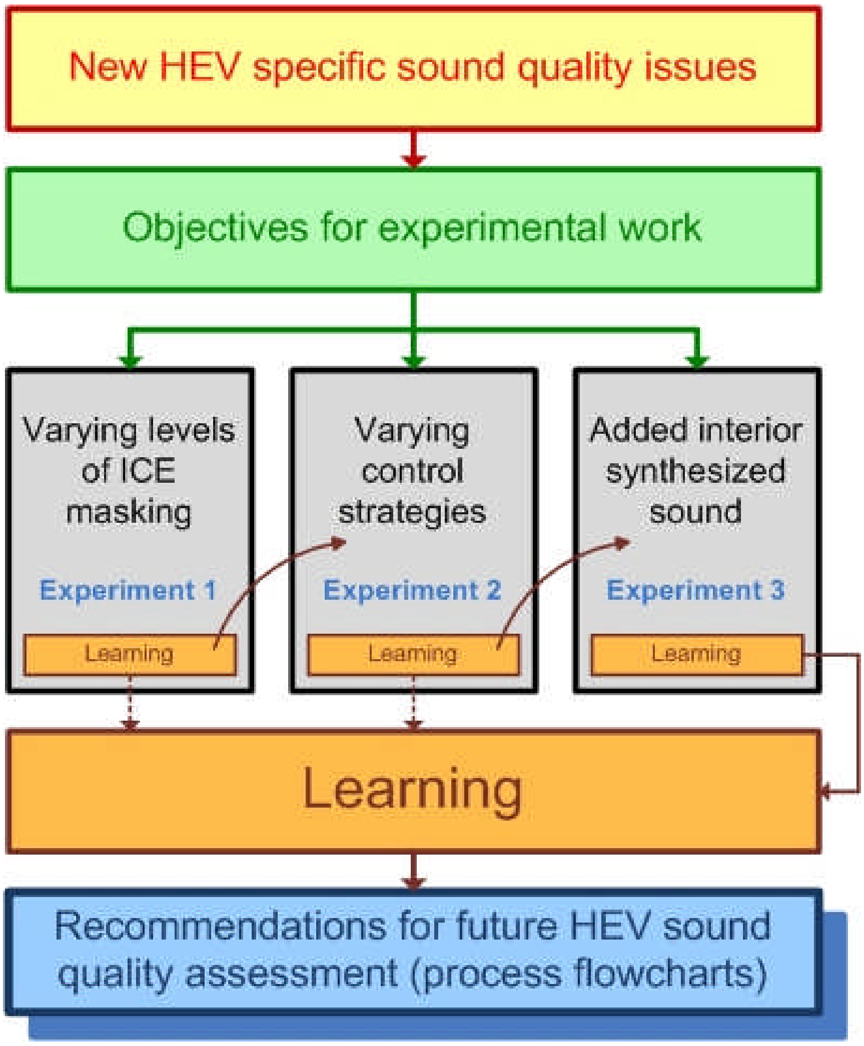

Figure 4.5 Process for Experimentation and Recommendation

As shown in figure 4.5, the three areas chosen to develop new interactive customer sound quality assessments were:

- ***Varying levels of ICE masking*** effect on customer perception - *refer to Submission 6(a)*

For the 1st assessment the sound pressure level (dB) of the ICE was to be altered for a selection of vehicle options (with the same configuration). It is interesting to see the effect this may have on customer perception, especially when the vehicle moves between key HEV operations (e.g. EV only to initial ICE assist) during a fixed repeatable drive cycle. Another consideration is the level of masking provided by the ICE of other unwanted noises (e.g. electronic switching) in conjunction with this. This will also be the first opportunity to recommend a suitable process for creating; running and analysing HEV related sound quality assessments (e.g. drive cycle selection and suggested stopping criteria).

- ***Varying control strategies*** effect on customer perception - *refer to Submission 6(b)*

For the 2nd assessment it is interesting to see if customer perception is effected for the same vehicle over identical driving conditions due to changes in the sound profiles because of varying initial conditions.

- ***Added interior synthesized sound*** effect on customer perception - *refer to Submission 6(c)*

Similar comparisons will be made in the 3rd assessment of HEV options and modified versions of the same HEV options with added synthesized conventional ICE sounds contributing to the overall vehicle sound profile. The understanding gained from such a review could also be used as a decision tool to support the inclusion of added interior synthesized interior sounds in HEVs or not.

These three areas were chosen as there were a number of issues relating to each that had the potential to be assessed through interactive NVH simulation. The issue of exterior sound of HEVs was initially identified but not considered in this case as the focus of interior sounds was well suited to interactive NVH simulation.

An initial pilot study for each assessment was carried out with 3 participants (suitable size in which to gauge an opinion of the suggested assessment structure and not time consuming) to review issues such as the content of the questionnaires (i.e. relevance of the questions in relation to the assessment) and the overall duration of the assessment (i.e. to ensure the attention and interest of the participants would be maintained). Further comments were to be captured upon completion of the assessments through post assessment questionnaires and discussions with the author. This was beneficial as more detailed responses to the questions asked and tasks given during the assessment could be captured and it allowed the participants to enhance their awareness and understanding of HEV sound quality related issues. The aim is to understand issues such as: whether future eco-friendly vehicle technology sound profiles need to be modified to sound more like conventional ICE vehicles, or whether the focus should be on aiding the shift of customer culture to embrace new eco-friendly vehicle technologies such as HEVs. Such decisions should take into account the effect this may have on other important factors such as driving style or impact on fuel economy.

4.3 Process for Creating the HEV Sound Quality Assessments

The process for creating the three assessments included a number of key steps. These steps included: selection and modification of existing jury evaluation and analysis techniques (e.g. semantic differential evaluation) for experimentation; selection of a suitable range and number of HEV options (sound stimuli) to present to participants during each assessment; and selection of HEV specific operations (i.e. transition between EV only mode to initial ICE assist), through representative fixed drive cycles.

The steps taken were classified into the following 3 key stages (which would later translate to the development of a recommended process tool):

- HEV model installation and validation
- Choice of initial HEV options to present to subjects
- Method and analysis selection

The key elements of the installation and validation stage are covered in more depth in Submission 4 which includes: installation of a HEV model (e.g. *Toyota Prius* case study) into an interactive NVH simulation environment and the initial validation of the HEV model sound replication. Through listening to the individual component sound profiles created and installed in the *B&K PULSE NVH Vehicle Simulator* software it was clear that the electric motor sound extracted from the original recordings was more dominant (more noticeable whining) when compared over the same drive cycles from the original full vehicle recordings. The reason for this may have been the result of the contribution from other component sounds which had not been properly extracted. Therefore, the base electric motor sound within the software was reduced by increments of 1 dBA (a-weighted sound pressure level) and then the HEV model sound profile dBA level was compared (dBA traces over time) against the originally recorded profile. The level at which the electric motor was closest to the original source was -7 dBA lower than it had originally been. The sound replication of the *Toyota Prius* model used was deemed suitable once the electric motor component had been lowered.

Initially there were sound contributions from other components noticeable which had not been filtered out during the model development process sufficiently. All of the assessments created and carried out followed the same generic structure. The key method and analysis choices made during the assessments are shown in figure 4.6.

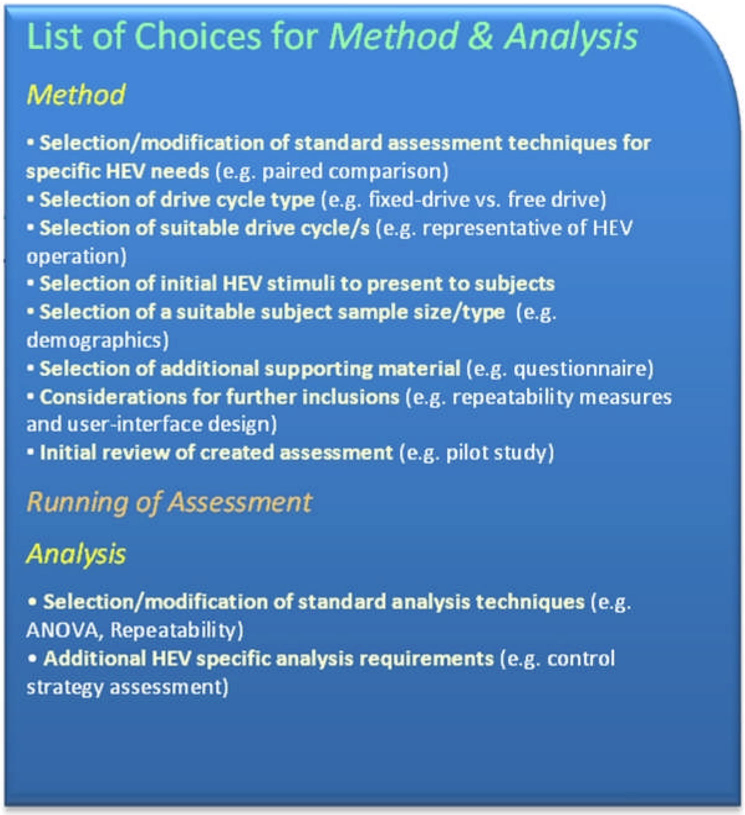

Figure 4.6 Method and Analysis Selection for HEV Sound Quality Assessment

The analysis carried out on each of the three assessments can be broken down into the following key steps:

- Standard analysis (e.g. ANOVA and repeatability); focused on observing the numbers and scores generated from the assessments.

- Additional analysis for each assessment (e.g. correlation of questionnaire responses with scores); focused more towards the specific details of the assessments, aiding the definition of a generic process carried out during all of the assessments…
- …leading onto the development of three process flowcharts encompassing the key steps undertaken within the three classed stages chosen initially as a recommendation tool.

Existing jury evaluation techniques including the paired comparison and semantic differential were reviewed (Submission 5) and used as a template for the creation of the three assessments. For each assessment there were individual specific selections made for each; for example the selection of a suitable set of HEV options with varying initial SoCs over the same drive cycle for the 2nd assessment (varying control strategies effect on customer perception).

Referring back to the representative HEV drive cycle (figure 3.5) used as an aid during the sound and vibration recording phase, in full this would not be suitable for sound quality assessment due to the length (1950 seconds) being far too long. *2nd Gear Wide Open Throttle* (2GWOT) has previously been used as a fixed drive cycle for conventional vehicle sound quality assessments due to its nature allowing for suitable and repeatable customer evaluations (Dunne, 2003). 2GWOT was deemed unsuitable as a fixed drive cycle or any vehicle operation for assessment of HEVs as the aggressive accelerational characteristics were not representative of HEV operation. Taking this into account the driving condition selection for the 1st assessment (varying levels of ICE masking) selected was of a constant 70% acceleration (relating to pedal loading, as read from the ECU throttle map to ensure repeatability) taken from a section of a test run during the sound recording phase.

One interesting area of HEV operation is between the *motor only* and *motor + initial ICE assist* phases. This resulted in the selection of the driving condition starting from 17 mph rather than from rest like 2GWOT. Prior to running the 1st assessment it was important to review the overall assessment (e.g. content and duration), supporting questionnaire and any other matters relating to it through conducting a pilot study. Recommendations were made upon completion of the pilot study which was carried out by 3 participants including splitting of the questionnaire into a prior and post assessment form.

Following on from the selection of a suitable driving condition the choice of vehicle options was the next step taken during each of the three assessments. For the 2nd assessment, (varying control strategies) 9 HEV options were selected; with an estimate of 1 minute per vehicle selection for each semantic this resulted in an estimated assessment time of 27 minutes (across all 3 semantics). As with the 1st assessment; less than 30 minutes was deemed a suitable duration in which to maintain a participants enthusiasm and concentration.

The chosen driving condition for the 2nd assessment (figure 4.7) was modelled in *ADVISOR* using the inbuilt *Toyota Prius* performance model and the relevant ICE speeds from the drive cycle were captured for a range of initial battery SoCs of 0.0, 0.5, 0.62, 0.8 and 1.0.

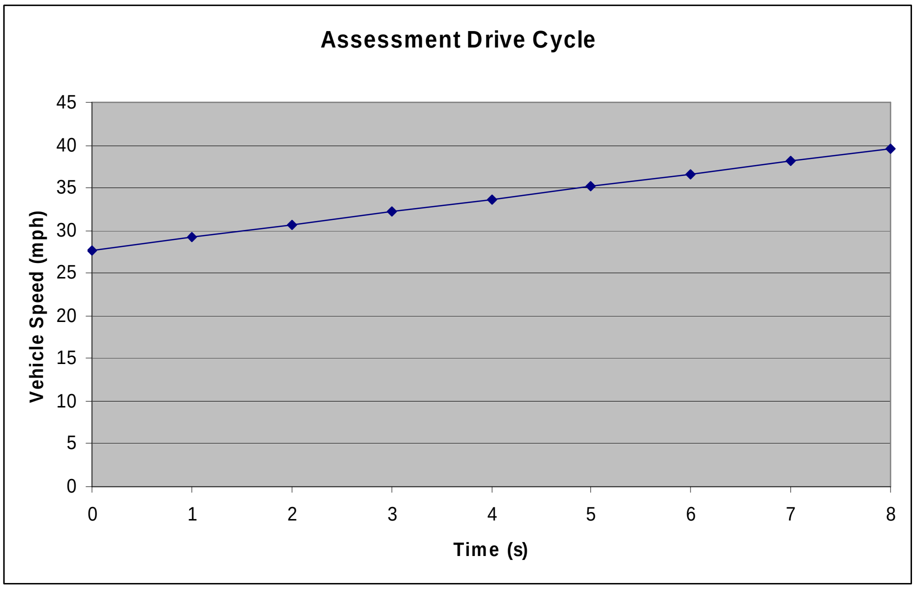

Figure 4.7 Chosen 2nd Assessment Driving Condition

Initial SoCs of 0 and 1.0 are unrealistic for real-world conditions yet they were chosen as it was possible to represent the theoretical limits of ICE operation for this given driving condition. An initial battery SoC of 0.62 was chosen as it is the level for which the control strategy of a *Toyota Prius* tends towards in order to maintain the battery's real state-of-health (SOH); lower than this for long periods of time can reduce battery life and higher than this can be a waste of fuel. Initial SoCs of 0.5 and 0.8 were chosen to expand the range between 0 and 1.0, resulting in varied ICE speed for the same vehicle speed (figure 4.8).

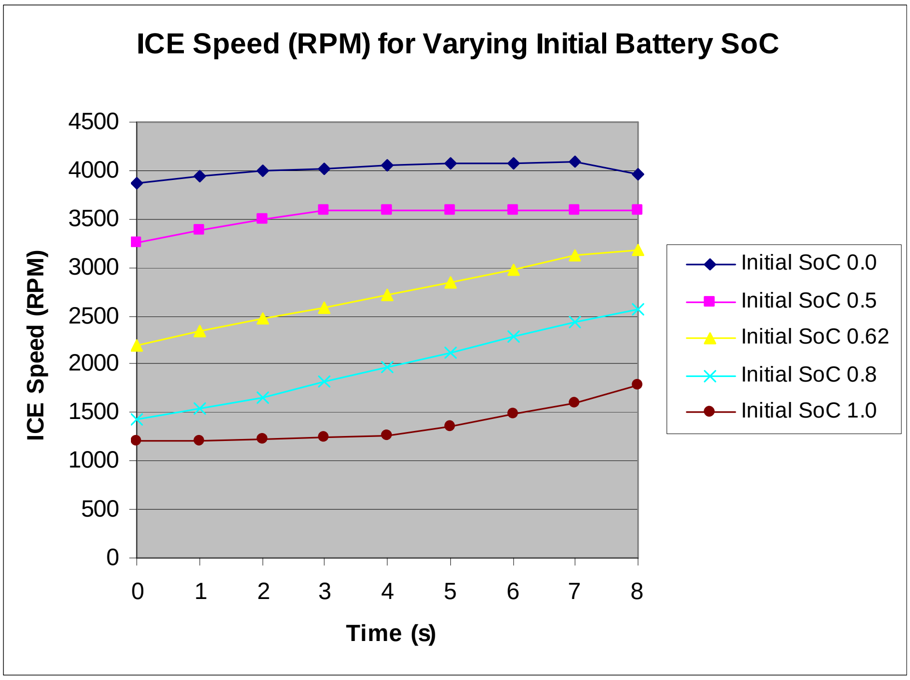

Figure 4.8 ICE Speed (RPM) for Varying Initial SoC

With five variations of initial battery SoC (0, 0.5, 0.62, 0.8 and 1.0) the following 9 HEV options were chosen:

1) ICE 0 (0.62 Initial SoC)
2) ICE 0 (0.0 Initial SoC)
3) ICE 0 (0.8 Initial SoC)
4) ICE -10 (0.5 Initial SoC)
5) ICE 0 (1.0 Initial SoC)
6) ICE 0 (0.5 Initial SoC)
7) No ICE 0 (0.62 Initial SoC)
8) ICE -10 (0.62 Initial SoC)
9) ICE 0 (0.62 Initial SoC)

HEV options 1, 2, 3, 5 and 6 used the reference *Toyota Prius* model and were selected to represent the full range of initial battery SoCs chosen, with 'ICE 0' referring to the fact that the sound level of the ICE had not been altered (referring back to the naming of the vehicle selections in the 1st assessment). HEV option 9 was an exact replica of vehicle selection 1 in order to have a measure of participant repeatability within this assessment (for scores across the three semantics). HEV options 1, 7 and 8 were chosen which utilised a representative *Toyota Prius* initial SoC (0.62) with varying levels of ICE masking; complementing the focus of the 1st assessment. Other HEV options where direct comparisons could be made due to fixed variables were: 4 and 6 where the initial SoC was 0.5 (with varying ICE masking) and 4 and 8 with varying initial battery SoCs and same level of ICE masking (-10dB compared to the reference source). The level of masking denoted as 'ICE -10' was chosen as it was one of the most preferred levels of ICE contribution from the 1st assessment. Further information of the 1st assessment (varying levels of ICE masking) can be found in Submission 6(a). Subsequent information relating to the other two assessments (varying initial control strategies and added interior synthesized sounds) can be found in Submissions 6(b) and 6(c).

The assessments themselves were carried out on the desktop version of the simulator with two adjacent screens; one which displays the driving environment (left-hand side of figure 4.9) and the other with the user interface with the relevant voting scales (right-hand side of figure 4.9). The screen shot shown in figure 4.8 is taken from the 3rd assessment (added interior synthesized sound); here the participant listened to 9 different vehicle options using a semantic differential rating scale to score them on three chosen semantics (*refinement, powerfulness and appeal*). The reason for selecting semantics for *powerfulness* and *refinement* was that previous conventional vehicle assessments through interactive NVH simulation have commonly used these (Dunne, 2003). Creating a better awareness of HEVs is an issue which arose from a review of literature as previously documented within the project (Submission 1) identifying such terms as: comfort, appeal and acceptance of such technologies. Through discussions carried out during the 1st assessment with participants, words relating to appeal were commonly used in reference to HEV technologies and were the reason for choosing an *appeal* semantic for this assessment. In having an additional semantic related to appeal of HEVs it was possible to correlate the responses on this semantic against the *powerfulness* and *refinement* semantics to see where on each scale the highest scores for appeal were situated. A powerfully perceived HEV with one initial condition (i.e. initial SoC of 0.7) may be as appealing as a perceived refined HEV with another initial condition (i.e. initial SoC of 0.4) for example.

Figure 4.9 Sample of Assessment Interface

The vehicle options chosen for the 3rd assessment consisted of a selection of conventional ICE vehicles, modified hybridised versions of existing conventional ICE vehicles, HEVs and a selection of HEVs with added synthesized note of a conventional ICE (refer to figure 4.9). Once participants had completed selecting their scores for a particular semantic they then moved onto the next screen until all three semantic screens were completed.

In terms of the prior knowledge of the selected participants some had previous experience of conventional vehicle sound quality assessments. Once the assessments were completed, the results were then stored and saved within the simulator software; later exported for analysis. For confidentiality purposes a standard disclaimer form was created and used for each of the three assessments.

4.4 Analysis of Assessments

Analysis of the three assessments was carried out to validate the approaches taken and results obtained. This included a review of time, effort (i.e. number of button clicks made by each participant) and participant repeatability for each of the three assessments. One key motivation was to discover whether varying HEV options could have a significant effect on the resulting sound profile (i.e. for the same driving condition) and whether this had an effect on customer perception. Therefore, the results themselves were also analysed, which could be as an aid for making objective decisions/changes; for example, modelling and synthesis of ICE sounds as a result of subjective based customer evaluations, as with a previous piece of work (Amman and Das, 2001).

Initially conventional analysis techniques were carried out for each of the assessments including: measures of repeatability and suggested stopping criterion. Further analysis was then carried out relating to the specific assessments themselves such as time and effort and correlation of questionnaire responses to the data.

A brief review of the analysis carried out during each of the three assessments is covered here for the following:

- Repeatability assessment carried out for the 1st and 2nd assessments
- Suggested stopping criterion carried out for the 1st assessment
- RMS dB difference between HEV options in relation to changes in repeatability carried out for the 1st assessment
- Time and effort review carried out for the 2nd assessment
- Correlation coefficients between the 3 semantics used for the 2nd assessment
- Questionnaire responses from the 2nd assessment
- Questionnaire responses from the 3rd assessment

The average merit scores given by all 22 participants who complete the 1st assessment for each of the 8 HEV options are shown in figure 4.10. The 5th option shown in figure 4.10 (A/B ICE 0) is identical to the original sound profile of the recorded *Toyota* Prius, where '0' indicates no change to the ICE sound level. For options 2 to 8 the ICE note has been modified (from -15 dB to +15 dB with increments of 5dB). Option 1 is effectively an EV version of the *Toyota Prius* (purely based upon the sound profile) as the ICE sound component has been taken out altogether.

Paired comparisons were made which include 10 repeated pairings in order to assess participant repeatability. Figure 4.11 shows the average merit scores for those who had repeatability scores of >=90%. In both cases the least preferred option was when the ICE sound level was +15 dB higher than the reference source. The preferred option changed from -5 dB (full set) to 0 dB (>=90% repeatability).

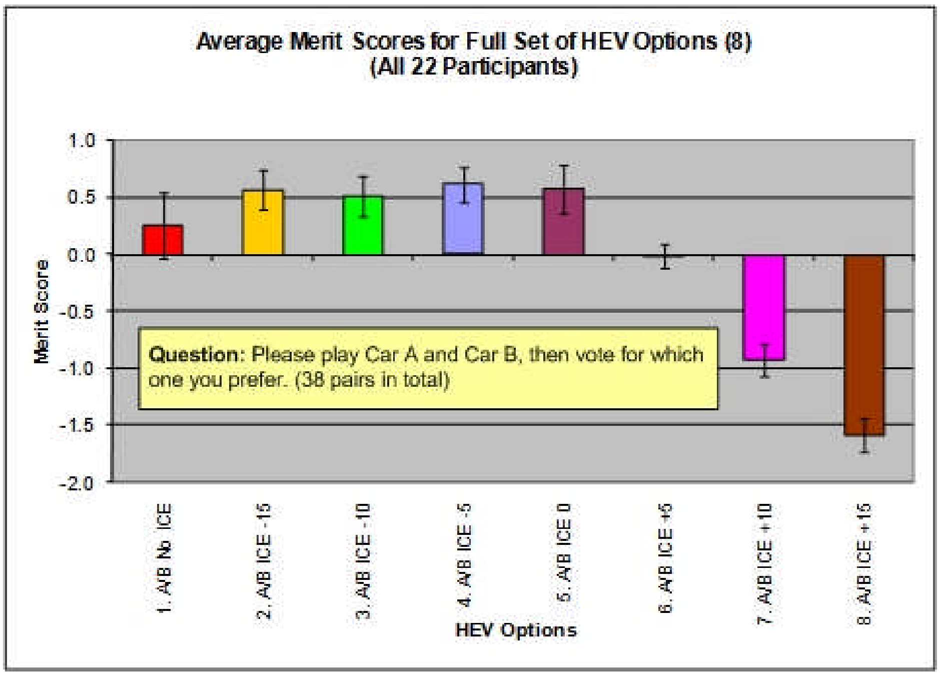

Figure 4.10 Average Merit Scores for Full Set of HEV Options (All 22 Participants)

The error bars shown in each case are of 1 standard deviation (based on the individual merit scores of each participant for each of the 8 HEV options chosen. Hence a significant increasing dislike for a higher ICE note (+5 dB to +15 dB). Even though the primary aim of creating and conducting this experiment was to trial the method for further related studies, the results showed that by lowering the ICE note slightly (by -5dB), had a positive effect on customer preference.

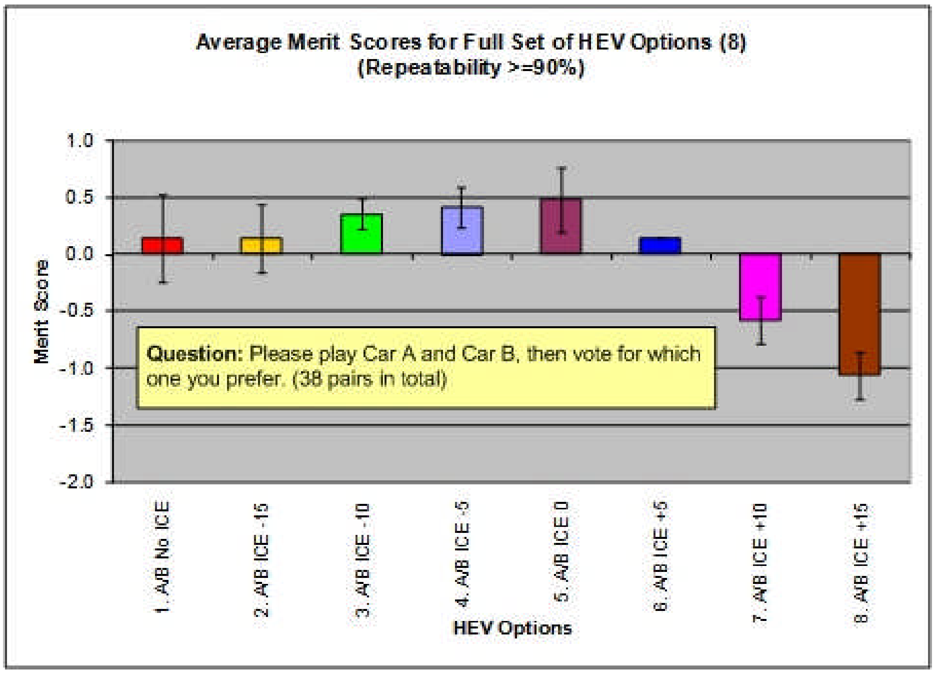

Figure 4.11 Average Merit Scores (Repeatability >=90%)

HEV Options	Repeated Answers?				
	>=60%	>=70%	>=80%	>=90%	Full Set
No ICE	0.33	0.30	0.27	0.14	0.26
-15	0.59	0.58	0.41	0.14	0.57
-10	0.50	0.52	0.66	0.35	0.51
-5	0.60	0.61	0.34	0.41	0.61
0	0.58	0.47	0.33	0.48	0.57
+5	0.05	0.04	-0.04	0.14	-0.02
+10	-0.94	-0.83	-0.79	-0.58	-0.93
+15	-1.71	-1.68	-1.17	-1.07	-1.58

Table 4.1 Preferred HEV Options for Varying Levels of Repeatability

Table 4.1 shows how the most and least preferred HEV options differed with respect to changing levels of repeatability. This presentation of scores is suitable for making a quick observation of the most and least preferred options in each case. A further breakdown of the individual participant repeatability scores can be referred to in appendix 9.3.

Merit scores obtained from the 1st assessment were analysed to recommend a suitable stopping criteria for further similar related studies. Figure 4.12 shows the change in overall merit scores for the 8 HEV options. The merit scores shown on the graph are the average scores of all of the participants who had completed the assessment at that given point (e.g. merit score at point D is the average after 4 participants had completed the experiment and the merit score for point P is the average after 16 participants had completed it). An initial observation showed that after the 14th/15th participants (N and M) had completed the assessment the average merit scores began to level out; indicating that the average scores for all participants were becoming less significantly different. Therefore, it was suitable to carry out a significance test to assess this.

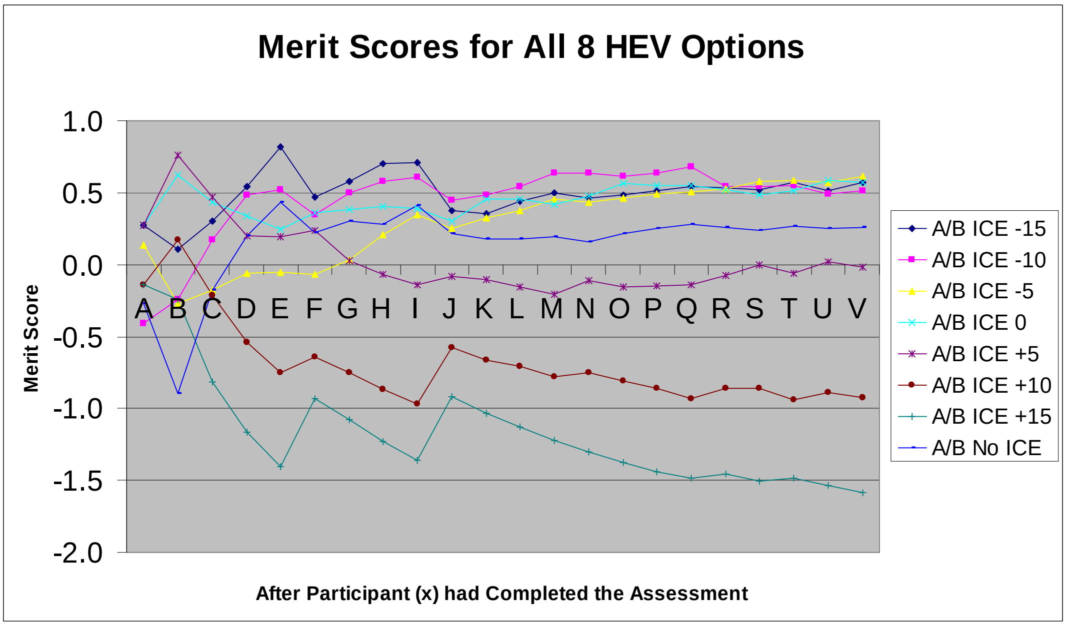

Figure 4.12 Merit Scores for All 8 HEV Options

The *t* distribution significance test was carried out on this data (as shown in appendix 9.4) which shows that after participant M had completed the assessment there was not a significant difference between the scores after M and those after all 22 participants had completed set. From using statistical tables for *t* distribution, *t* should be less than 1.721 with a 95% confidence level (sample size of 22). Figure 4.13 supports the selection of 14 participants as a suitable sample size for this case and similar studies; as shown in more detail in appendix 9.4.

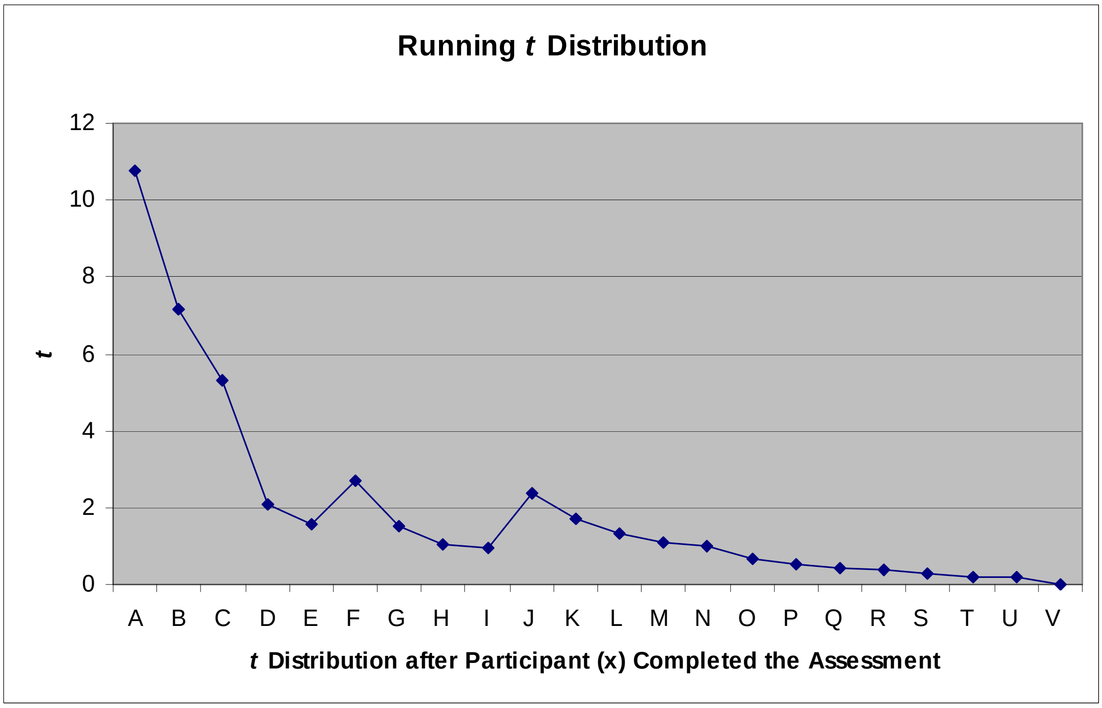

Figure 4.13 *t* Distribution after each Participant Completed the Assessment

This method was expanded further to take into account a change in order of when participants completed the assessment. Figure 4.14 shows the same selection of 22 participants with the order randomised. For this changed order the smoothing of the graph occurs again yet the *t* distribution analysis indicates the suitable stopping criterion would be after the 17th participant (P) had completed the assessment (refer to appendix 9.5 for detailed breakdown of scores). This method was repeated ten times, with the highest stopping criterion still 17; and therefore the recommended sample size for the assessment.

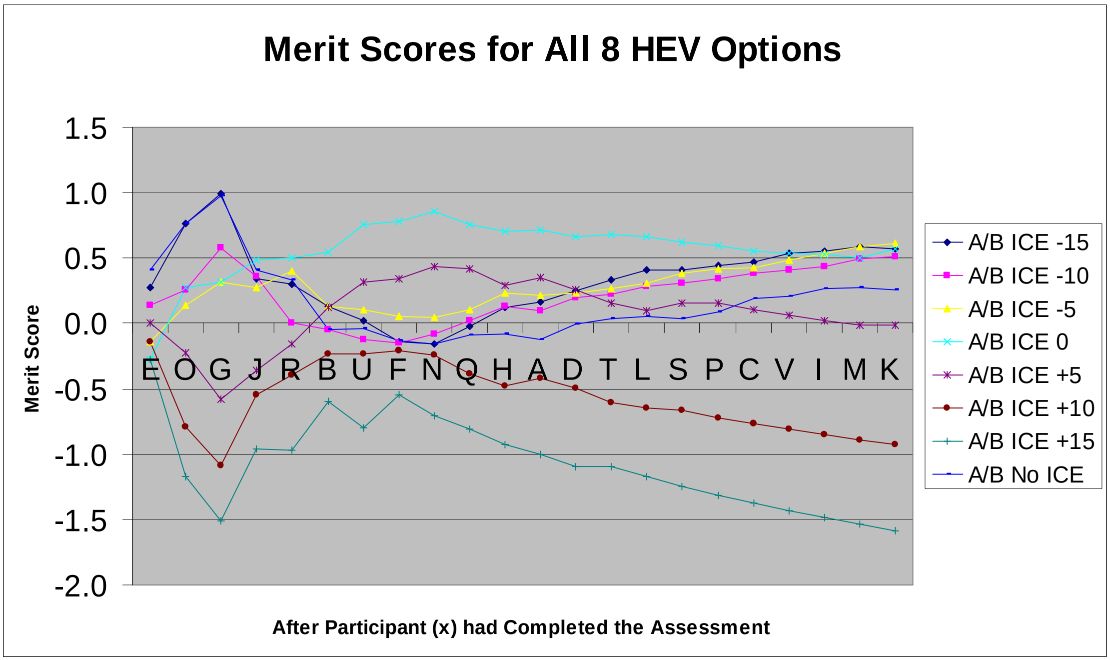

Figure 4.14 Merit Scores for All HEV Options (Changed Order)

Additional more specifically related analysis was carried out during the 1st assessment which included: assessing the relationship between the RMS dB difference between the 10 repeated pairs. The reason for this was to see if the difference in the overall sound level between a pair had an effect on how repeatable the participants were.

Table 4.2 shows the overall RMS dB levels for each of the 8 HEV options from the 1st assessment. The difference in overall RMS dB was then taken for each of the 38 paired selections presented to the participants during the assessment (as shown in appendix 9.6).

The resulting graph (figure 4.15) shows that when the RMS dB difference (factor) between the paired selections increased, repeatability also increased. For the full set of 22 participants the average repeatability score was 70.9%; as shown by figure 4.15 the repeatability increased to 79.9% (for >=0.25 RMS dB difference between pair), 83.6% (>=0.5), 83.6% (>=1.0), 86.4% (>=2.0) and 88.7% (>=4.0) respectively. This review strengthens the understanding of the relationship between individually paired options.

HEV Options	Overall RMS dB	
	Left	Right
ICE -15	87.9	87.0
ICE -10	88.1	87.0
ICE -5	88.5	87.5
ICE 0	89.5	88.6
ICE +5	91.3	90.6
ICE +10	94.9	94.2
ICE +15	99.3	98.7
No ICE	88.3	87.2

Table 4.2 RMS dB Levels for each HEV Option

The analysis carried out for the 1st assessment fulfilled the objective of wanting to find out whether a variety of ICE sound levels within the same HEV configuration had an effect on customer perception. The results shown here have shown that the perception was influenced by a change in ICE note.

For this assessment a driving condition was chosen which made a transition between two key HEV operations (EV only to initial ICE assist). The overall preference for all participants was positioned between options 3 and 5 (-10 dB to 0 dB difference compared to the originally recorded ICE sound level). This suggested that a lower ICE note than -10 dB did not sufficiently mask out other irritating sounds and higher than 0 dB resulted in a discomforting step change in sound profile between the two HEV operational regions.

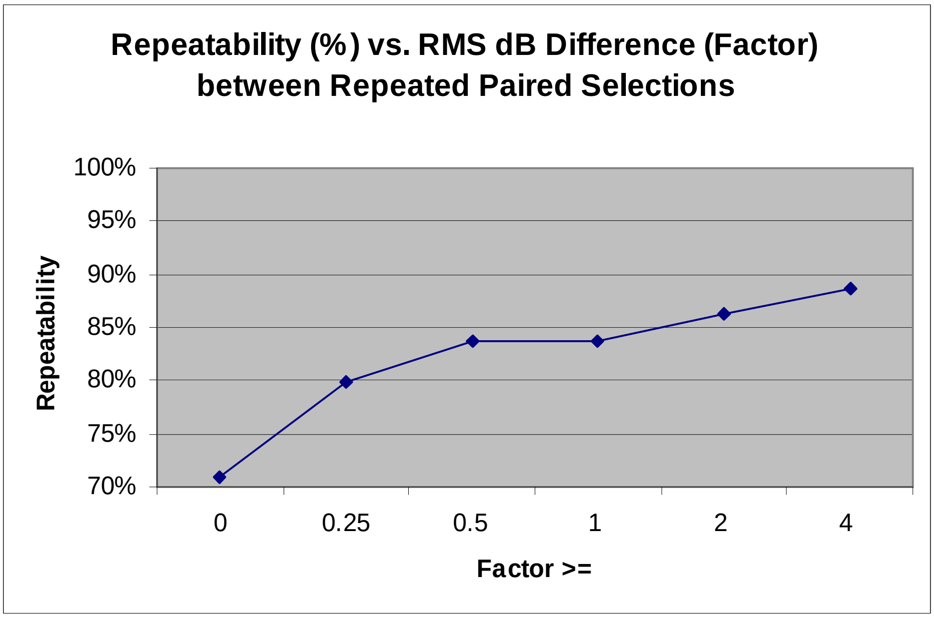

Figure 4.15 Repeatability vs. RMS dB Difference (Factor) between Selections

The time and effort taken by participants to complete each of the three assessments was reviewed. As an example, table 4.3 shows a snapshot of the results taken during the 2nd assessment. The data taken for each participant included: running time (s), time for each action (s) and the number of times each HEV option was played. Such results and information were used as a means of validation for the suitable duration and ease of use for this assessment. The understanding gained from this review was taken into account for the following assessment. The full breakdown of time and effort data for participant C which includes the full *refinement*, *powerfulness* and *appeal* semantic information can be referred to in appendix 9.7.

Semantic	Participant					
	C					
	Running Time (s)	Time for Action (s)	Action	Car No.	Value	Times Played
Refinement	0	0	Select Word Pair			
	14	14	Select Car	Car 1		1
	25	11	Rating	Car 1	6.5	
	26	1	Select Car	Car 2		1
	30	5	Rating	Car 2	2	
	39	9	Select Car	Car 3		1
	44	6	Rating	Car 3	7	
	48	3	Select Car	Car 4		1
	52	4	Rating	Car 4	6.5	
	56	4	Select Car	Car 5		1
Average		5.6				
Total		56.0				

Table 4.3 Snapshot of Time and Effort Data

The number of button clicks participant C took to complete the assessment was 110 (see table 4.4). In terms of the overall time taken for each action this was 5.8 seconds; this does include listening to the HEV options which all had duration of 8 seconds. The time taken to complete the assessment was 10.7 minutes which was far less than the previous conservative estimate of 27 minutes as a suitable maximum duration (based upon 1 minute for each of the 9 HEV options across three semantic screens). The split of time taken between each of the three semantics was quite evenly split (*refinement* 34.0%, *powerfulness* 36.7% and *appeal* 29.3%). More time was taken on the *powerfulness* semantic (yet this was not significantly greater), which could suggest that this was the hardest semantic to score the HEV options for. This is supported by the breakdown of actions taken by participant C (table 4.5) where the HEV options were listened to 26 times in total; 4 more than during the *refinement* semantic which was the next closest.

Number of Actions (Button Clicks)	**110**	
Average Time/Action (s)	**5.8**	
Running Time (s)	**639.6**	
Running Time (mins)	**10.7**	
Time Spent on Refinement Semantic (s)	**217.7**	34.0%
Time Spent on Powerfulness Semantic (s)	**234.8**	36.7%
Time Spent on Appeal Semantic (s)	**187.1**	29.3%

Table 4.4 Time and Effort Results for Participant C

Table 4.5 shows that the majority of HEV options were played 2/3 times by participant C. The most played HEV option was 9 on the *powerfulness* semantic (5 times), this could be due to the fact that participant C identified that options 1 and 9 were identical (for repeatability assessment); scoring them both 4.0 as shown in appendix 9.7.

HEV Options	No. of Times Played/Semantic			Total
	Refinement	Powerfulness	Appeal	Across All Semantics
1. ICE 0 (Initial SoC 0.62)	3	3	2	8
2. ICE 0 (Initial SoC 0.0)	3	3	2	8
3. ICE 0 (Initial SoC 0.8)	2	2	2	6
4. ICE -10 (Initial SoC 0.5)	2	3	2	7
5. ICE 0 (Initial SoC 1.0)	2	2	2	6
6. ICE 0 (Initial SoC 0.5)	4	2	2	8
7. No ICE (Initial SoC 0.62)	2	3	3	8
8. ICE -10 (Initial SoC 0.62)	2	3	3	8
9. ICE 0 (Initial SoC 0.62)	2	5	2	9
Total	22	26	20	68
Average	2.4	2.9	2.2	8

Select Car	68
Rating	38
Select Word Pair	3
Save & Exit	1
	110

Table 4.5 Breakdown of Actions for Participant C

Number of Actions (Button Clicks)	132	
Overall Average Time/Action (s)	6.5	
Overall Average Running Time (s)	858.6	
Overall Average Running Time (mins)	14.3	
Average Time Spent on Refinement Semantic (s)	306.5	35.7%
Average Time Spent on Powerfulness Semantic (s)	340.9	39.7%
Average Time Spent on Appeal Semantic (s)	211.2	24.6%

Table 4.6 Time and Effort Results for Full Set

The average time taken for the assessment by all 22 participants was 14.3 minutes as shown in table 4.6; this result supports the suitability of the assessment in terms of overall duration. Most time was spent on the *powerfulness* semantic (39.7%) with each HEV option played on average 3.3 times compared to 3.0 and 2.3 for the *refinement* and *appeal* semantics respectively (see table 4.7). In terms of participant effort (number of clicks) the average was 132 clicks as shown in table 4.7. The majority of the clicks were for playing the HEV options (78 times) and then for scoring them (50 times). When asked, all participants said that the effort required and taken was suitable.

HEV Options	Average No. of Times Played/Semantic			Total
	Refinement	Powerfulness	Appeal	Across All Semantics
1. ICE 0 (Initial SoC 0.62)	5	5	3	13
2. ICE 0 (Initial SoC 0.0)	2	2	1	5
3. ICE 0 (Initial SoC 0.8)	3	3	2	8
4. ICE -10 (Initial SoC 0.5)	3	2	2	7
5. ICE 0 (Initial SoC 1.0)	2	3	2	7
6. ICE 0 (Initial SoC 0.5)	3	4	3	10
7. No ICE (Initial SoC 0.62)	3	3	2	8
8. ICE -10 (Initial SoC 0.62)	2	3	3	8
9. ICE 0 (Initial SoC 0.62)	4	5	3	12
Total	27	30	21	78
Average	3.0	3.3	2.3	9

Select Car	78
Rating	50
Select Word Pair	3
Save & Exit	1
	132

Table 4.7 Breakdown of Actions for Full Set

The results gained from reviewing the time and effort aid further related studies through new understanding such as: suitable selection of the number of HEV options to present to participants, number of semantics to choose and consideration for the overall duration of the assessment (in order to maintain the concentration and enthusiasm of participants throughout the whole assessment). This step will be represented in the process flowcharts (relating to the key steps taken during these studies) as a means of recommendation for others to consider and/or carry out.

The correlation coefficients between each of the three semantics (*powerfulness*, *refinement* and *appeal*) used during the 2nd and 3rd assessments was analysed. The reason for doing this was to see where on the *powerfulness* and *refinement* scales a vote based upon *appeal* for each HEV options sat. The scores from the 2nd assessment (appendix 9.8) resulted in the highest scored (highlighted green) and lowest scored (highlighted red) results as shown in table 4.8.

HEV Options	Semantic		
	Refinement	Powerfulness	Appeal
1. ICE 0 (Initial SoC 0.62)	4.7	4.2	5.7
2. ICE 0 (Initial SoC 0.0)	1.7	6.7	3.2
3. ICE 0 (Initial SoC 0.8)	5.8	3.6	6.3
4. ICE -10 (Initial SoC 0.5)	7.4	4.2	5.5
5. ICE 0 (Initial SoC 1.0)	7.4	1.8	5.0
6. ICE 0 (Initial SoC 0.5)	3.8	7.0	4.2
7. No ICE (Initial SoC 0.62)	6.8	3.5	5.8
8. ICE -10 (Initial SoC 0.62)	7.7	4.0	6.5
9. ICE 0 (Initial SoC 0.62)	5.0	4.4	5.6

Table 4.8 Highest and Lowest Scores for each Semantic

In terms of the correlation between each of the three semantics the highest and least scored HEV options (8 and 2 respectively) are the same for both the *refinement* and *appeal* semantics. This supports the initial observation of similar trends in the scores for both. As shown the highest and least scored HEV options were 6 and 5 respectively for the *powerfulness* semantic. The one deemed most powerful had the loudest ICE note with an initial SoC of 0.5 whereas the one perceived to be the least powerful had the same ICE note yet an initial SoC of 1.0. This resulted in there being a larger EV only operation period and later and shorter period of ICE assistance. The most appealing option and most refined option had the same level of ICE note as the most preferred during the 1st assessment (ICE -10 dB lower than the original *Toyota Prius* level) with the standard *Toyota Prius* initial SoC. The least appealing/refined was HEV option 2, which had 0.0 initial SoC; so the ICE note was dominant throughout the whole driving condition due to no EV only operation. An initial SoC of 0.0 is unrealistic and was chosen as previously mentioned to cover the full theoretical window of initial SoC. Table 4.9 shows the conversion of these scores to the rank; supporting the identified similarities in the trends of the *refinement* and *appeal* semantics.

HEV Options	Semantic		
	Refinement	Powerfulness	Appeal
1. ICE 0 (Initial SoC 0.62)	7	4	4
2. ICE 0 (Initial SoC 0.0)	9	2	9
3. ICE 0 (Initial SoC 0.8)	5	7	2
4. ICE -10 (Initial SoC 0.5)	2	5	6
5. ICE 0 (Initial SoC 1.0)	2	9	7
6. ICE 0 (Initial SoC 0.5)	8	1	8
7. No ICE (Initial SoC 0.62)	4	8	3
8. ICE -10 (Initial SoC 0.62)	1	6	1
9. ICE 0 (Initial SoC 0.62)	6	3	5

Table 4.9 Rank Order of Average Scores for each Semantic

Tables 4.8 and 4.9 represent the average scores very well with little consideration for variations between the individual scores. Table 4.10 expands upon this to show the average of the individual ranking scores. As before the most and least preferred options are the same across all three semantics with the addition of option 2 being the most *powerful* option in conjunction with option 6 as before. To review this even further the variances between the individual scores have been shown in table 4.11. A variance of less than or equal to 1 is highlighted in light green and greater than 1 and less than 2 in orange. As shown the majority (23 out of 27, 85%) of the variances between the individual scores is less than 2. This shows that HEV options were scored pretty similarly across all semantics by each of the 22 participants.

HEV Options	Semantic		
	Refinement	Powerfulness	Appeal
1. ICE 0 (Initial SoC 0.62)	6.1	4.6	4.0
2. ICE 0 (Initial SoC 0.0)	**8.8**	**1.6**	**8.0**
3. ICE 0 (Initial SoC 0.8)	4.9	6.0	3.3
4. ICE -10 (Initial SoC 0.5)	2.5	4.8	4.6
5. ICE 0 (Initial SoC 1.0)	2.6	**8.1**	5.6
6. ICE 0 (Initial SoC 0.5)	7.2	**1.6**	6.7
7. No ICE (Initial SoC 0.62)	3.3	5.8	3.6
8. ICE -10 (Initial SoC 0.62)	**2.1**	4.8	**2.7**
9. ICE 0 (Initial SoC 0.62)	5.8	4.5	4.2

Table 4.10 Average of the Individual Rank Scores for each Semantic

HEV Options	Semantic		
	Refinement	Powerfulness	Appeal
1. ICE 0 (Initial SoC 0.62)	**1.7**	**1.2**	**1.0**
2. ICE 0 (Initial SoC 0.0)	**0.8**	**1.4**	**1.1**
3. ICE 0 (Initial SoC 0.8)	**0.9**	**1.3**	**1.3**
4. ICE -10 (Initial SoC 0.5)	**1.5**	**1.3**	2.2
5. ICE 0 (Initial SoC 1.0)	**1.3**	**1.3**	2.9
6. ICE 0 (Initial SoC 0.5)	**1.6**	**1.3**	3.0
7. No ICE (Initial SoC 0.62)	**1.0**	**1.1**	**1.6**
8. ICE -10 (Initial SoC 0.62)	2.1	**1.8**	**1.1**
9. ICE 0 (Initial SoC 0.62)	**1.7**	**1.8**	**1.8**

Table 4.11 Variance of Scores for each Semantic

Powerfulness and *refinement* have been used for previous conventional sound quality vehicle assessment previously as mentioned. They are representative of automotive sound evaluations and are independent of one another. The additional *appeal* semantic used in this case could be used in conjunction with these two as a measure of acceptance or preference. In terms of the correlation scores between each of the three semantics they were:

- Refinement vs. Appeal = 0.78
- Powerfulness vs. Appeal = -0.67
- Refinement vs. Powerfulness = -0.81

As shown the *appeal* and *refinement* semantics had a correlation score of 0.78. Therefore, in this case a highly refined HEV option was very appealing. The correlation between the *appeal* and *powerfulness* semantics was -0.67; a highly powerful HEV option being very unappealing. If the assessment was on a selection of sporty conventional ICE vehicles for example this may have been the other way round. *The refinement* and *powerfulness* semantics were also highly uncorrelated with a score of -0.81. In summary the most appealing HEV option based upon this assessment were more refined than powerful. The additional axis provided by the *appeal* semantic is useful for introducing new vehicle technologies such as HEV; when using conventional target maps such as *powerfulness* vs. *refinement*.

Questionnaires were created and used during all three assessments. The comments given in most cases supported what was determined from the results. As an example, the comments given by all 22 participants (A to V) for question 1.1 *('Please briefly describe how you made your decisions during the test?')* on the post-assessment questionnaire used during the 2nd assessment were categorised as shown in table 4.12. Refer to appendix 9.9 for a more in-depth breakdown of participant responses to this and all other questions asked during the 2nd assessment.

Comments relating to decisions made during the test:	**Engine note/sound**	**Softer sound more appealing**
	A + N	B, K + P
	Less/lacking in power	**Clear difference**
	C + D	D
	Refinement semantic easier	**Appeal semantic easier**
	C	F, G + R
	Selections were more refined	**Preferred more refined**
	D	D
	Re-order button useful/used	**Initial votes were close**
	E, H, L, Q, S + U	E
	Word pairings (extremes)	**Level of sound**
	J + R	O
	Focused on visuals	**Perception of vehicle speed**
	I	I
	More constant vehicle sound better	**Selections more refined than powerful**
	T	V

Table 4.12 Comments Relating to Decisions Made During the Assessment

The results had already suggested that the HEV options perceived to be the most refined were also more appealing; comments given such as: "softer sound more appealing" and "preferred more refined" supported this assumption. What was mentioned most was the usefulness of the *re-order* button (6 related comments); this supports the decision to include this as a functionally. The *re-order* button allowed participants to rearrange the HEV options into descending order based upon their current scores. This allowed participants to refine initial scores by listening to closely placed options again.

The comments themselves were then broken down into the following three classes, as some comments were focused on usage (method and semantic related) and some on preference, all important but very different in nature (see table 4.13):

- Usage/Method Related
- Semantic/HEV Option Related
- Preference Related

	Usage/Method Related	Semantic/HEV Option Related	Preference Related
Classing of comments:	Engine note/sound	Less/lacking in power	Softer sound more appealing
	Clear difference	Refinement semantic easier	Preferred more refined
	Reorder button useful/used	Appeal semantic easier	More constant vehicle sound better
	Initial votes were close	Selections were more refined	
	Word pairings (extremes)	Selections more refined than powerful	
	Level of sound		
	Focused on visuals		
	Perception of vehicle speed		

Table 4.13 Classing of Comments Relating to Decisions Made During the Test

As shown most comments related to the usage and method itself which could be used to improve the assessment for further runnings. This process helped to further develop the author's understanding of creating, running and assessing HEV refinement related assessments. For example, the comments relating to the preference of the HEV options (i.e. softer sound more appealing) supports the high correlation (0.78) between the *refinement* and *appeal* semantic scores. In terms of the variety of HEV options in this assessment comments such as "clear difference" suggests that there was a suitable selection.

Another example of the questionnaire results providing useful information was from the 3rd assessment. Out of four options: *conventional ICE* (highlighted red), *HEV* (highlighted green), *EV* (highlighted orange) and *unsure* (highlighted blue); participants had to choose which best represented each of the 9 vehicle options listened to during the assessment (refer to appendix 9.10 for a full breakdown). The results were categorised as shown in table 4.14.

Vehicle Options	Responses Given for Each Vehicle Option			
	Conventional ICE	HEV	EV	Unsure
1. ICE 0 (+ Car 1 ICE Sound)	12	**7**	0	3
2. Car 2	**15**	4	0	3
3. Car 2 + EM (-10)	10	**7**	0	5
4. ICE -10	2	**11**	6	3
5. Car 1	**10**	8	0	4
6. ICE 0 (+ Car 2 ICE Sound)	9	**7**	0	6
7. No ICE	0	10	**8**	4
8. Car 2 + EM (-2)	11	**6**	0	5
9. ICE 0	2	**11**	5	4

Table 4.14 Responses Given for Each Vehicle Option

The numbers in bold (red and green in colour) in each case are the actual vehicle technologies of the options presented (with regards to the overall vehicle sound profile). The numbers highlighted green are those which have correctly received the most votes by the participants. It is interesting to see that the two conventional ICE vehicle options (2 and 5) received the highest scores for being conventional ICE vehicles. The only other two options which were correctly identified as HEVs by receiving the most votes were the two options (4 and 9) which were the only two HEV options which need not have added interior synthesized sound of a conventional ICE (example of option 4 shown in figure 4.16). Refer to appendix 9.11 for the full selection of plots for each of the 9 vehicle options.

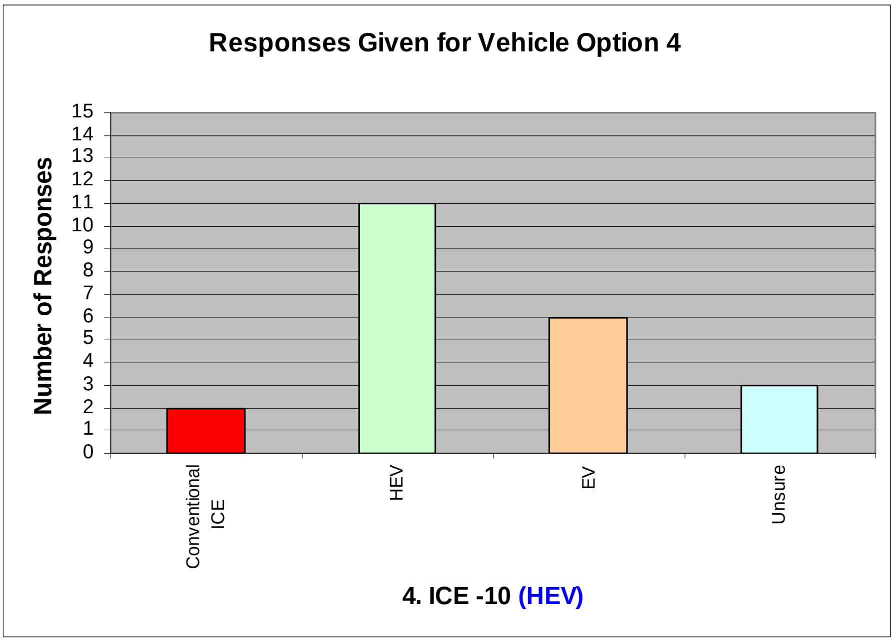

Figure 4.16 Responses Given for Vehicle Option 4

The vehicle options which were incorrectly scored were 1, 3, 6, 7 and 8. Options 1, 3, 6 and 8 were those which had added interior synthesized conventional ICE sounds for an HEV and added EM sound for conventional ICE options. All four of these options were considered as HEVs in this case as each had sound contributions from an ICE (2 ICEs in some cases) and EM. It is interesting to see that participants considered all four of these options as conventional ICE vehicles. This suggests that those who more prefer the sound of a conventional ICE vehicle are more inclined to like HEVs with added interior synthesized sounds of conventional ICEs. The final option was 7 which was the only EV in the set. The majority of participants (10) considered option 7 to be a HEV, yet there was no ICE sound. This suggests that the perception of what a HEV is in this case is where the ICE is less dominant or unconventional in terms of the resulting vehicle sound profile.

For more depth relating to the analysis and findings carried out for each of the three assessments please refer to Submissions 6(a), 6(b) and 6(c).

4.5 Discussion of Assessments

Referring back to the objectives for these experiments, one of the motivations for doing these was to learn how to select driving conditions which were representative of HEV operation. Once conventional ICE vehicle driving conditions were deemed unsuitable (e.g. 2GWOT due to its aggressive nature) for assessment of HEVs, driving conditions were created which were more representative of HEV operation. In this case a less aggressive constant acceleration drive cycle was chosen (70% pedal loading - as read from the ECU throttle map during the sound and vibration recording phase). An important feature for HEVs is the transition between the EV only to the initial ICE assist phase. Therefore for these experiments a drive cycle was chosen which moved between these regions, rather than starting from rest as a 2GWOT typically does. This gave a suitable set of vehicle sound profiles and related customer perceptions and discussions for each of the three assessments.

Another motivation for doing these assessments was to find out whether varying HEV options (e.g. with different initial battery SoC) could have a significant effect on the resulting vehicle sound profile over the same driving condition and therefore have an effect on customer perception. Leading on from an initial review of representative and real-world drive cycles a selection of HEV options were chosen for each of the assessments. In each case there were differences in the resulting overall vehicle sound profiles. The results shown and discussed within this report have shown that these differences (minor in some cases) can have both a positive and negative impact on customer perception of HEVs.

A review of the 1st assessment for example (varying levels of ICE masking) suggests that the sound pressure level (dB) of the ICE alone was not directly proportional to a positive or negative level of perception (refer to figures 4.10 and 4.11). During the transition from EV only operation to initial ICE assist, there is an increase in the ICE sound, which could cause discomfort to the driver if the ICE sound pressure level is too high; whereas a smoother transition (lower ICE note) in sound between key operations may be more pleasurable. In conjunction with this the higher the ICE sound pressure level (dB) the more irritating sounds such as electronic switching are likely to be masked out as the ICE is one of the most dominant sound sources within a vehicle (dependent upon speed).

Throughout these experiments it has been beneficial to analyse results such as time and effort, and repeatability. The decision making process of the participants was also reviewed through a breakdown of their questionnaire responses. The methods created and understanding gained from these assessments are used as a recommendation aid for further related studies through the inclusion of the key steps taken during these assessments in the form of process flowcharts. The flowcharts created in this case for each of the three experiments are summarised in the following section.

4.6 Development of Recommended Process for HEV Sound Quality Assessment

In conjunction with the key steps chosen and carried out for creating, running and analysing each of the three experiments, a recommended process to aid others (i.e. NVH engineers) was created through three flowcharts. These related to the three key stages (*HEV model installation and validation*; *Choice of initial HEV options to present to subjects* and *Method and analysis selection*) classified at the beginning of the experimentation phase (discussed previously in section 4.3). Both generic and case study related (*Toyota Prius*) process flowcharts were created as shown in appendices 9.12 to 9.17. These three flowcharts can be summarised by the recommended process shown in figure 4.17. Referring back to the methodology (HEV refinement assessment process) in figure 3.1; this is an output from the *Validation* stage. This recommended process could be used as an aid by OEMs or sound specialists as a means for improving HEV sound quality for further related studies. Each of the 7 stages highlighted in figure 4.17 are now discussed.

In order to create a HEV model for interactive NVH simulation (Stage 1 - *HEV model creation and installation* in figure 4.17), new methods are required during the sound and vibration recording process. HEV specific issues relating to their refinement (e.g. information from sound and new specific sources) present new challenges as discussed in section 2.2. Prior to the recording phase, key factors that affect the perception of sound within a HEV needed to be identified (as in figure 3.2). In addition to the traditional sound and vibration recording instrumentation, extra vehicle data logging equipment should also be considered. In this case additional data logging equipment was used to capture vehicle and component speeds in synchronisation with the sound and vibration recording. This made it possible to create a representative control strategy within the HEV model (as highlighted previously in figure 3.6).

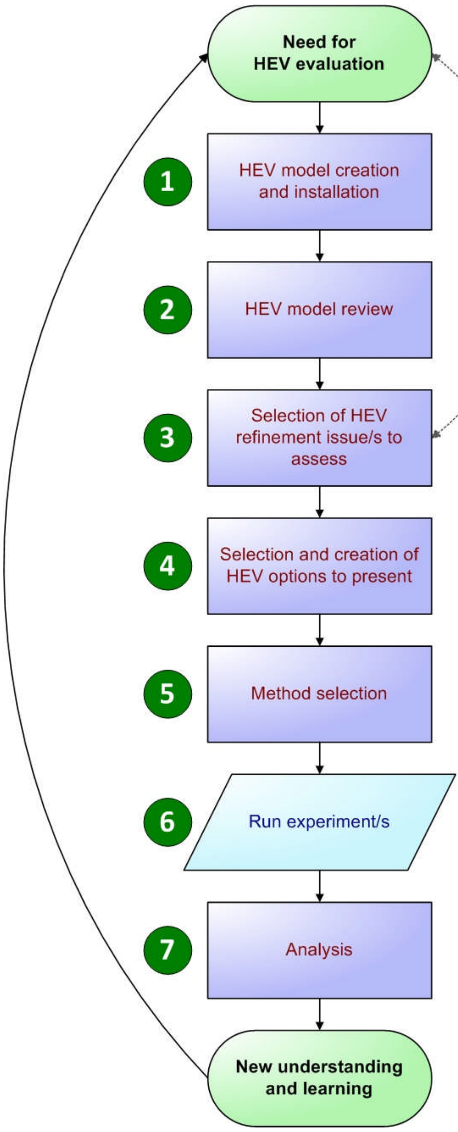

Figure 4.17 Recommended Process for HEV Sound Quality Assessment

Stage 2 *(HEV model review)* was carried out and is an important consideration to ensure that the HEV model created is suitable for experimentation. Individual lookup tables were created in this case for the ICE only, electric motor only and combined sound profiles. The option of switching between these tables was possible (option within the fixed drive cycle file), which made it possible to alter the effective vehicle control strategy (in relation to the sound profile). Additionally, more complex control strategy options could be achieved by generating component data from simulation modelling software (e.g. *ADVISOR* in this case) as shown by figure 4.8 for example (varying ICE speeds due to different initial battery SoCs over the same fixed drive cycle). The HEV model and software itself could be improved to deal with more complex control strategy options but in this case was deemed suitable due to the possibility of importing externally created information. The key consideration for any experiments is that the HEV model created is fit for purpose (i.e. suitable representation of real world operation).

The s*election of HEV refinement issue/s to assess* (Stage 3) came as a result of reviewing the current practice for HEV refinement during this project (refer to section 2.1.4). These issues should be and were categorised (refer to section 2.2) and later reduced to a final set of three issues (varying levels of ICE masking, varying control strategies and added interior synthesized sound effect on customer perception); these three interior sound based issues were chosen as they were suitable for interactive NVH simulation (the chosen approach – refer to section 2.4).

For stage 4 *(selection and creation of HEV options to present)* HEV options could be based upon an initial set of targets or in this case a representative (varied) set to explore the particular HEV related sound quality issue/s chosen. Considerations must be given on the spread and range when choosing HEV options. An extreme option could result in a contrasting score being given for that particular option with the other (more alike) options scores converging (discussed in more detail in Submission 5).

As with traditional sound quality assessment of conventional vehicles, there are considerations for the selection of a suitable method for HEV evaluations (Stage 5 – *Method selection*). Method options considered and chosen in the case of the 3 experiments included: selection of suitable jury evaluation technique/s (semantic differential evaluation and paired comparison), selection of fixed over free drive cycles (to reduce complexity and ensure route was fixed for all HEV options), suitable sample size (for participants and HEV options) and suggestions for suitable stopping criteria (using *t*-distribution). All potential methods are discussed in more detail in Submissions 5. Additionally, more specific HEV related information was and can be captured through supporting questionnaires.

The following stage (Stage 6 – *Run experiment/s*) is the action based upon the selection of suitable methods and HEV options to assess. It is important to conduct a pilot study prior to a full study to ensure that aspects such as duration, functionality and focus are as planned when conducted. This also allows for any minor and/or major modifications to occur based upon an initial set of feedback from representative participants.

Analysis was carried out on each of the three experiments (Stage 7 – *Analysis*) to validate the approaches taken and to summarise the learning outcomes (as discussed in section 4.4). Standard analysis techniques were reviewed and used which included: repeatability assessment and correlation coefficients of semantic scores. An additional semantic called *appeal* was chosen in this case (2^{nd} and 3^{rd} assessments) in addition to the traditional *powerfulness* and *refinement* semantics; as used in previous conventional vehicle assessments (Dunne, 2003). The *appeal* scores in conjunction with the questionnaire responses made it possible to learn more about the participants' perceptions of HEVs. Additional more specific analysis such as those mentioned must be carried out to learn more about the specific HEV issues being assessed in relation to customer perception.

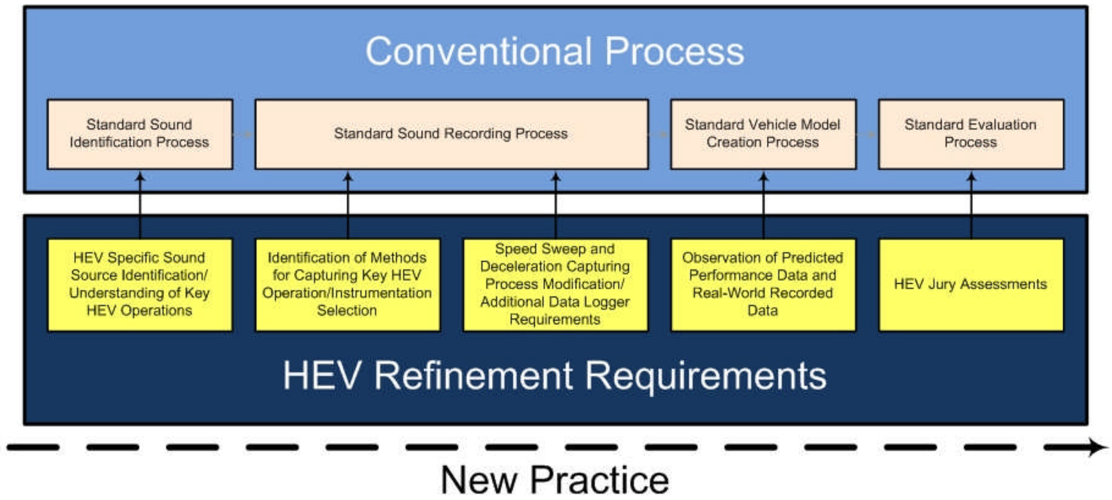

Figure 4.18 New Practice for HEV Refinement Assessment

In summary, the recommended process created can be used by OEMs or sound specialists as a means for improving HEV sound quality. The creation of process flowcharts supported the final objective of capturing the learning and recommendations in a usable form to aid further related studies (from section 4.2). Referring back to the HEV refinement assessment process (figure 3.1) the recommended process contributes (HEV jury evaluation block) to the overall recommendation for new practice for HEV refinement assessment as shown in figure 4.18.

5 Discussion

Within this chapter a brief update on HEV technology developments in relation to the work in this project and a review of the benefits from this project to OEMs and providers of simulator technologies and key innovations are discussed. The following chapter highlights the opportunities leading on from this project for further research and development.

5.1 Update on Related HEV Technology Developments

With the current global economic downturn, the development of a low-carbon economy has been considered an integral part of providing economic recovery (Morley, 2008). Such occurrences has seen European car manufacturers ask for aid from the European Union to help develop *green* vehicle technologies (£35.73bn) (Gow, 2008). The aim is to encourage the development of eco-friendly vehicle technologies and cut CO_2 emissions. An example of support being offered to industry within the UK in building competitive advantage in the global shift to a low carbon economy has been the introduction of *Cenex* (Evans, 2008). *Cenex* are the UK's first Centre of Excellence for low carbon and fuel-cell technologies. Such centres can support a range of OEMs and SMEs for innovation of lower carbon emissions solutions from vehicles of all types.

A proposal was recently introduced (4th March 2008) in Kentucky, US (HB732) to direct the *Transportation Cabinet* to declare regulation establishing a minimum sound standard for HEVs (Overly, 2008). This proposal means that HEVs sold in Kentucky after 1st August 2010 would have to comply with this standard. Such characteristics of the standard have been addressed during this project (added interior/exterior synthesized sound) which includes: the vehicle to omit sound similar to a conventional ICE vehicle during idling. Other HEV related sound work has seen *Lotus* develop a system called *Safe and Sound* which was designed to mimic the sound of a conventional ICE through artificial noise (Berman, 2008). The sound produced by the device changes frequency with vehicle speed in order to simulate current engine sounds.

Sound quality of HEVs is an area which is continually rising in interest; as identified in this project through a review of *academic literature*; *HEV car reviews* and *online blog feedback*. Since the beginning of this project other examples of work focused on HEV sound quality assessment have been published (Pears, 2008; Nielsen, 2009). The outputs from this work have included the development of new methods for sound quality assessment of HEVs and newly acquired knowledge. This project provides a solid platform for further related work at a time when interest, market penetration and customer awareness/acceptance of hybrid vehicle technologies is growing.

5.2 Industrial Benefits

The methods developed and understanding gained from this research project has included: classification of HEV specific sound quality issues, identification of key factors that affect the perception of sound within a HEV, recommendations for modifications to the conventional sound recording process for HEV specific requirements and validation of a HEV interactive NVH model through related sound quality assessments. This has led to a number of benefits to the supporting partner companies involved with this project.

Referring back to the HEV refinement assessment process (figure 3.1), *B&K's* main involvement with the project was during the *creation and approval phase* leading onto *new practice*. The three assessments created were carried out in the *B&K PULSE NVH Vehicle Simulator*; validating the use of such an environment for specific HEV refinement related assessments. Other key benefits achieved by *B&K* from this work have been:

- Improved understanding of HEV specific sound source identification.
- The key learning from the project including the effect varying initial conditions (i.e. battery SoC) can have on the resulting HEV sound profile. This has been used as a platform by *B&K* for discussing noise and vibration in HEVs (a new phenomena) especially with Japanese automotive companies including Honda (Brüel & Kjær, 2008).
- The methods created and used during this project for a HEV case study have been used as a direct link for running further studies with *B&K* on hybrid vehicles and other eco-friendly technologies (e.g. electric vehicles). An example of this is through a major project within the author's group (WMG, the University of Warwick) called APPRAISE *(Appropriate Product Representations for Assessment in Structured Evaluations)*; focused on improving the effectiveness and efficiency in decision making during product development based on the results of subjective evaluations in real world assessment and structured evaluations (Brüel & Kjær, 2007).

Current and future opportunities for *B&K* have been supported by this project as mentioned, with a clear company focus of further developing sound quality assessment of HEVs; as supported by the advertisement placed in the March 2008 issue of

Automotive Testing Technology International entitled *Setting NVH Targets in Design of Hybrids* (appendix 9.18).

During the *Toyota Prius* case study, new specific methods were developed by *Sound Evaluations Ltd* for capturing sound and vibration data from a HEV based upon the recommendations given by the author including: key factors that affect the perception of sound within a HEV and instrumentation for sound, vibration and additional data logging requirements (i.e. electric motor speed). Particular involvement with *Sound Evaluations Ltd* sat primarily within the *recording phase* of the HEV refinement assessment process (shown in figure 3.1) leading into the *creation and approval phase* where the *Toyota Prius* information captured was used to create a HEV model for implementation into the interactive NVH simulator. Other key benefits achieved by *Sound Evaluations Ltd* from this project have included:

- First experience of recording a HEV and creating a model for interactive NVH simulation; and associated learning which included:
    - The requirement to record additional vehicle information (e.g. through *CANBus* link) simultaneously with sound and vibration data for basic control strategy development (i.e. component switching).
    - A new strategy for recording HEVs for use in an interactive NVH simulator.
        - Necessity of quiet location/time on the track.
- Development of a new technique for replaying the sound of a HEV in fixed-driving mode to enable simulation of the sounds which would be experienced by driving any known course, in any driving style, and with any cost function (with external logic simulation provided through output from *ADVISOR* {in this case} of the HEV switching system to generate the parameters for the various drivetrains).

- Three individual look up tables for the ICE, electric motor and combined created. Through the sound profile alone it was then possible to modify the effective control strategy of the HEV options being used.
- Further project and early plans for developing artificial external noise packages for HEVs, considering aspects such as: pedestrian safety and perception of brand quality. As identified during the early stages of this project but not explored in this case (section 2.2).

Sound Evaluations Ltd is now utilising the tools and understanding gained from this project and are currently in the process of starting a selection of new projects with other industrial partners for further sound quality assessment of HEVs. Validation of the HEV model developed in this project through conducting the three assessments has ensured *Sound Evaluations Ltd* that the method used to develop the model provides a realistic representation for interactive NVH simulation. *Sound Evaluations Ltd* have recently carried out a similar process for the sound and vibration recording of a selection of electric vehicles as part of the APPRAISE project as mentioned earlier.

5.3 Additional Benefits

Additional benefits and dissemination to other internal/external partners included:

- The sound and vibration recording process carried out on the *Toyota Prius* worked in conjunction with another project's requirements within the *University of Warwick*. The other project was focused on the development of WARPSTAR *(Warwick Powertrain Simulation Tool for Architectures)*; a project which provided proof of a number of hybrid vehicle concepts (Walker, et al, 2006), collaborating with over 50 industrial partners including: *JLR*, *Amberjac* and *Dennis Eagle*. The sound, vibration and additional vehicle data (i.e. ICE speed and GPS) required from the *Toyota Prius* for both projects was able to be captured during the same period of testing at the *Millbrook* test and development track.

- A review of the project including a run though of the developed methods and associated case study of the *Toyota Prius* was presented to a selection (≈ 15 people) of NVH and hybrid vehicle related engineers at *Jaguar & Land Rover (JLR)*. New areas of understanding from the project were communicated to the engineers, highlighting a number of new HEV specific refinement related issues which had not previously been understood and/or considered within *JLR*.
- Since the beginning of this project three *Integrated Manager Development Scheme* (IMDS) Master’s level modules have been developed within the *University of Warwick* and ran for a number of industrial based representatives. The three modules developed included one entitled *Hybrid System Technologies* with material being provided for the specific refinement issues and new understanding related to HEV assessments relating to the learning and new methods developed within this project. Similar material has also been included in the newly created one-day workshop entitled *Hybrid Vehicle Technology Overview* which operates on a very similar basis.
- A paper relating to this project (Poxon, Jennings and Allman-Ward, 2008) was presented at the *Hybrid & Eco-Friendly Vehicle Conference 2008* (HEVC’08); sponsors included the *IET*, *IMechE* and *Cenex*. Acceptance cited a high quality relevant piece of research from a respected research group. This paper and related material has since been presented to the *Transport for London* (TfL) and used as an aid in the development of a new transport strategy for London.

6 Recommendations for Further Work

The completion of this project has presented opportunities for further work within the area of sound quality assessment of HEV. Three key areas for potential development are discussed during this section, which has been split into research and development.

6.1 Research

During this project three assessments were carried out focused on learning more about HEV related refinement issues and sound quality assessment of HEV technologies. For each assessment a representative HEV driving condition was chosen for participants to listen to and score a selection of HEV options for. Moving on from using fixed driving conditions for interactive NVH simulation, a HEV model could be improved to allow participants the opportunity to drive a selection of HEV options with free drive conditions. Rather than a backwards facing model with fixed drive cycle input a forward facing model with driver input (i.e. throttle and brake pedal inputs) could allow for investigations into new areas such as driveability (i.e. switching between key HEV operational modes and the effect this may have on driver comfort); and the resulting effect varying vehicle sound profiles have on the way participants drive and subjectively assess a selection of HEV options. Such approaches would be very useful to understand more about the response of the driver to a variety of HEV options in relation to other issues such as CO_2 emissions. Understanding from such studies could be used to consider the impact final HEV selections may have on customer appeal, driveability and performance. The methods created and used during this project could be reproduced for other eco-friendly vehicle technologies related studies such as for EVs and hydrogen fuel-cells. Currently, a new major project within the author's group is being proposed to develop new techniques for the sound quality assessment of EVs. This project aims to focus on interior and exterior sound assessment of EVs. Exterior sound of HEVs was identified as an issue during this project (i.e. regarding pedestrian safety and customer perception of brand quality) yet only interior sound of HEVs was explored. Exterior sound assessment development is important for HEVs and even more so for EVs due to the lower overall levels of vehicle sound. Further developments could aim to enhance the character of such technologies at a time when the market penetration of eco-friendly vehicle technologies and customer expectations are increasing.

6.2 Development

The user interface of the interactive NVH simulator software is tailored towards conventional ICE vehicle sound quality assessment. Specific HEV related additions were introduced during this project which included: the inclusion of specific HEV components in the model library (e.g. EM) and more complex driving condition data (e.g. representation of varying initial battery SoCs). Further work could be carried out to develop the user interface to include more specific HEV information. Suggestions have been made in appendix 9.19 for potential additions/changes to the interfaces. These include the addition of a HEV hierarchical diagram (rather than just a list of components), an indicator showing the current battery SoC during the assessments and a button which would allow participants to switch to EV only mode (see example of potential changes in figure 6.1).

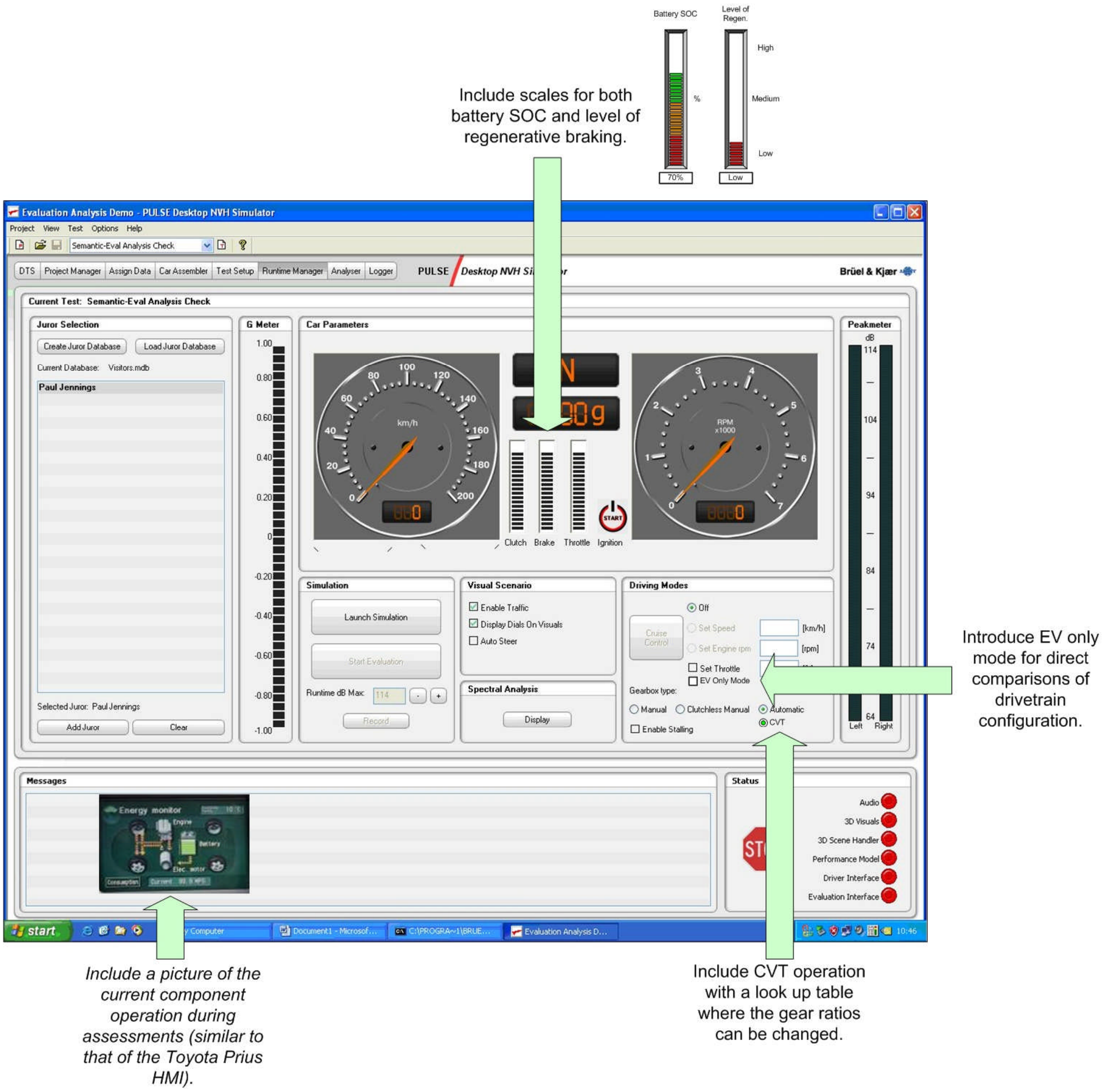

Figure 6.1 Suggested HEV Related Changes to User Interface

In addition to changes with the user interface it would also be beneficial to have a database application underlying within the simulator software so that project partners (and other component manufacturers/suppliers) can replace and modify existing HEV components; with the aim to build up a component library for future HEV development.

7 Conclusion

The introduction of HEVs has raised many new sound quality related issues (e.g. harmonic issues between ICE and electric motor) which were not previously evident within conventional ICE vehicle equivalents. These issues have been identified during this project from academic literature and car reviews from HEV users.

A number of approaches were reviewed to tackle them and interactive NVH simulation was chosen as a suitable approach because it can be used for real-time assessment of the sound of both current and future vehicle designs within an appropriate context. However, it was still uncertain whether this conventional ICE vehicle focused approach could be used for HEV specific requirements. An initial review of the process for sound quality assessment of conventional ICE vehicles was carried out. As a result it was necessary to modify this process, tailoring it for specific HEV needs, both in terms of the alternative sound sources and the more complex operation of the vehicle. An interactive HEV model was then successfully built, and has now been used in a real-world case study of a *Toyota Prius* for a number of sound quality evaluations.

The key motivation for doing this work was to provide industrial partners with new tools and understanding of HEV sound quality assessment. *Brüel & Kjær*, which has supported this project, has benefitted from the new methods developed and used during this project and the understanding gained from this work as a platform for creating opportunities for further related work with a selection of key players in the area of hybrid vehicle development.

The three assessments created and carried out have addressed new HEV related refinement issues of varying ICE masking, varying control strategy and added interior synthesized sound effect on customer perception. Key steps taken during the assessments included: the selection of representative driving conditions and vehicle options to present to participants. The driving conditions chosen were non-aggressive as this was more representative of HEV usage, as opposed to traditional evaluation conditions such as 2GWOT. A 2GWOT for example would bring the ICE in earlier due to higher vehicle torque demands, making it harder to make comparisons between key operations such as EV only and initial ICE assist regions.

Analysis was carried out both on the results and the responses given by participants captured through a selection of questionnaires. It was also important to learn about the decision making process of the participants in addition making judgements based upon the results alone. This was achieved by reviewing the breakdown of individual actions carried out by the participants when assessing the time and effort required for the assessments (i.e. possible to see when and in comparison to what other HEV options participants changed their original scores). Through conducting an overview briefing after each assessment it was beneficial to learn more about how each participant was making their decisions and basing their preferences during the assessments (supported by the questionnaire responses). The understanding gained from each in terms of the process taken and learning gained was used for the following assessment; resulting in a generic set of learning outcomes from the three assessments. Learning outcomes included: discovering that varying HEV options had a significant effect on the resulting vehicle sound profile and therefore had an effect on customer perception (e.g. preference for reduced ICE note of -5 dB on the *Toyota* Prius and significant changes in preference of the same HEV, over the same driving condition with varying initial battery SoC) and generally participants felt the more appealing HEV options were those perceived more refined than powerful in this case. This led to recommendations for future HEV sound quality assessments through the creation of process flowcharts.

Opportunities have been identified for further research and development, as a result of the methods developed and trailed during this project. Potentials for further work identified include: development of a forward facing HEV model to consider the impact of the driver on (focused on driver input into a HEV model rather than from fixed drive cycles in order for a more dynamic approach), improvements to the software user interface (tailoring it more towards HEV and other eco-friendly vehicle assessments) and using the processes created and validated during this project for other eco-friendly vehicle technology sound quality assessments.

The development of a forward facing HEV model is actually being carried out within a new project called *Sustainable Action on Vehicle Energy* (SAVE) a project on which the author of this report is now working. The focus of the project is to create tools and aid decision making for future eco-friendly vehicle technologies (including HEVs) to promote understanding and reduction of energy usage in the transport sector.

An interactive HEV model has been successfully built, and has now been used in a number of sound quality assessments. The process carried out has been documented as a selection of flowcharts and can be used by OEMs or sound specialists as a means for improving HEV sound quality.

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9 Appendices

9.1 Pugh Matrix of HEV Related Modelling Packages

Vehicle Areas	Individual Data	Advance 1.0	Advisor 2.1 (2002)	Advisor 2004	CarSim 6	Cruise	ErbSim	HVEC	Lotus	Modelica	MSC.Easy5	PSAT	Saber	SimDriveline 1	Simplev	Most Suited Package	Most Suited Package for Category
		HEV Related Modelling Packages															
Vehicle Purpose	Type of Service	S	S	DATUM	+	S	S	S	S	S	S	S	S	S	+	Simplev	Advisor 2004
	Maximum Speed and Acceleration	-	S		S	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Range	S	S		+	S	S	S	S	S	S	S	S	S	+	Simplev	
	Gradability	-	S		-	S	+	-	-	-	-	S	-	-	-	ErbSim	
	Payload (e.g. Air Conditioning)	-	S		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
Vehicle Configuration	Powertrain	S	-		-	S	-	-	-	+	-	-	S	-	-	Modelica	Advisor 2004
	EV or HEV	-	-		-	S	-	S	S	S	-	S	-	-	S	Advisor 2004	
	Series or Parallel Configurations	-	-		-	-	-	-	-	-	-	S	-	-	-	Advisor 2004	
	ZEV Range	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	Charge Sustaining or Charge Depleting	-	-		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Chassis Systems	+	S		S	S	S	S	S	S	S	S	S	S	S	Advance 1.0	
Vehicle Dynamics	Vehicle Forces	S	S		+	S	+	S	S	S	S	S	S	S	S	ErbSim/Carsim 6	CarSim 6
	Power and Torque	+	S		+	S	S	S	+	-	-	-	-	+	-	SimDriveline 1	
	Vehicle Weights and Capacities	S	S		+	S	S	S	S	S	S	S	S	+	S	CarSim 6	
Vehicle Performance	Maximum Speed	S	S		+	S	S	S	S	S	S	S	S	S	S	CarSim 6	Advisor 2004
	Acceleration and Deceleration Conditions	-	S		-	-	S	-	-	-	-	-	-	-	-	Advisor 2004	
	Range	S	S		+	S	S	S	S	S	S	S	S	S	S	CarSim 6	
	Gradability	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	Fuel Economy (mpg)	-	S		S	S	S	S	-	-	-	S	-	-	S	Advisor 2004	
	Emissions (e.g. CO2, Nox, etc.)	-	-		-	S	-	S	-	-	-	S	-	-	S	Advisor 2004	
	Dynamometer	S	S		S	S	S	S	+	S	S	S	S	S	S	Lotus	
Journey and Driver Data	Drive Cycles (Peak, Cruise and Average Powers)	-	S		-	S	-	-	S	-	-	-	-	-	S	Advisor 2004	Advisor 2004
	Prediction of Control Actions on Components of the Drivetrain	-	-		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Human Response	-	-		-	+	-	-	-	-	-	-	-	-	-	Cruise	
Transmission Data	Transmission Modelling (e.g. CVT)	-	-		-	S	-	-	-	-	-	-	-	S	-	Advisor 2004	Advisor 2004
	Differential and Number of Gears	+	S		S	+	S	S	+	S	S	S	S	+	S	Cruise/Lotus	
	Default Efficiency	+	S		S	S	S	S	S	S	S	+	S	S	S	PSAT	
ICE Information	Basic ICE Choice	S	S		S	S	S	S	S	-	+	S	S	S	S	MSC.Easy5	Advisor 2004
	Alternative APUs (Fuel-cell, Diesel Engine, etc.)	+	S		S	S	S	S	S	S	S	S	+	S	S	Saber	
	Alternative Fuels (e.g. Hydrogen, CNG, etc.)	S	S		S	S	S	+	S	S	S	S	S	S	S	Advance 1.0/HVEC	
	ICE Scaling	-	-		S	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	ICE On-off Control and Modelling	-	S		-	-	-	-	S	-	-	-	-	S	-	Advisor 2004	
	Idle Stop Feature	-	S		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Hydraulics	+	S		S	S	S	+	S	S	S	S	+	S	S	Saber	
Electric Motor Information	Basic Electric Motor Choice	S	S		-	-	-	-	-	S	-	S	-	-	S	Advisor 2004	Advisor 2004
	Alternative Electric Motor Technologies (e.g. Switched Reluctance, AC Induction, etc.)	S	-		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Motor Control and Torque Prediction	-	S		-	-	-	-	S	-	-	-	S	-	-	Advisor 2004	
	Electric Motor Assist	-	S		-	-	-	-	-	-	-	S	-	-	-	Advisor 2004	
Battery Information	Basic Battery Choice	S	S		-	-	-	-	-	-	-	-	-	-	S	Advisor 2004	Advisor 2004
	Alternative Battery Technologies (e.g. Lead-acid, Nickel Metal Hydride, etc.)	-	-		-	-	-	-	+	-	-	-	-	-	-	Lotus	
	Maximum Power	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	Capacity	-	S		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	

Information	State-of-Charge (SOC)	-	-		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Discharge	-	S		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
	Advanced Storage Technologies (Ultra-capacitors, Flywheels, 42-V etc.)	-	-		-	-	-	S	-	+	-	-	-	-	-	Modelica	
Wheel and Tyre Information	Wheel and Tyre Modelling	S	S		S	-	+	-	S	-	-	-	-	S	-	ErbSim	ErbSim
	Mass	-	-		S	-	S	-	S	-	-	-	-	-	-	Advisor 2004	
	Gyration Radius	S	+		+	S	+	S	S	S	S	S	S	S	S	ErbSim	
	Rolling Radius/Inertia	-	S		S	-	+	-	S	-	-	-	-	S	-	ErbSim	
	Rolling Resistance Coefficient	-	S		S	-	+	-	S	-	-	-	-	-	-	ErbSim	
Energy Considerations	Efficiency	S	S		S	S	+	S	S	S	S	+	S	S	S	PSAT	Advisor 2004
	Energy and Power Densities	S	S		S	S	S	S	S	S	S	S	S	S	+	Simplev	
	Levels of Regenerative Braking	-	-		-	-	-	-	S	-	-	-	-	-	-	Advisor 2004	
Control Parameter Strategies	Scalable Control Strategy	-	S		-	S	-	-	-	-	-	-	-	-	-	Advisor 2004	Advisor 2004
	Sensitivity	-	S		-	-	-	-	-	-	-	-	-	-	-	Advisor 2004	
NVH	Refinement	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	Advisor 2004
	Sound Quality	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	System Integration	S	S		S	+	S	S	S	S	S	S	S	S	S	Cruise	
Other Key Realities	Manufacturability	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	Advisor 2004
	Price and Availability	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	Maintainability	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
	Safety	S	S		S	S	S	S	S	S	S	S	S	S	S	Advisor 2004	
Modelling Package Compatibility	Graphical Interface	S	S		S	-	-	-	S	-	-	-	S	-	-	Advisor 2004	Advisor 2004
	High Speed Execution	-	S		S	-	-	-	-	-	-	-	-	-	S	Advisor 2004	
	Integration with Other Programs	S	S		S	-	S	-	-	S	-	-	S	-	-	Advisor 2004	
	Matlab/Simulink	S	S		S	S	-	-	-	S	-	S	-	S	-	Advisor 2004	
	Excel	S	S		+	S	+	S	S	S	S	+	S	S	S	ErbSim	
Variance with Datum		-22	-14	0	-19	-24	-22	-30	-21	-30	-36	-27	-31	-28	-29		

HEV Related Modelling Software Packages	Advisor 2004	Advisor 2.1 (2002)	CarSim 6	Lotus	Advance 1.0	ErbSim	Cruise	PSAT	SimDriveline 1	Simplev	HVEC	Modelica	Saber	MSC.Easy5
Rank Order of Number of Features	0	-14	-19	-21	-22	-22	-24	-27	-28	-29	-30	-30	-31	-36

HEV Related Modelling Software Packages	Advisor 2004	CarSim 6	ErbSim
Number of Vehicle Areas Most Suited for	13	1	1
Percentage of Coverage	86.67%	6.67%	6.67%

9.2 Identification of Gaps in the Current HEV Related Modelling Packages

Vehicle Areas	Individual Data	HEV Related Design Modelling Packages														Total Number of Packages Which Account for This Requirement
		Advance 1.0	Advisor 2.1 (2002)	Advisor 2004	CarSim 6	Cruise	ErbSim	HVEC	Lotus	Modelica	MSC.Easy5	PSAT	Saber	SimDriveline 1	Simplev	
Vehicle Purpose	Type of Service				✓										✓	2
	Maximum Speed and Acceleration		✓	✓	✓											3
	Range				✓										✓	2
	Gradability		✓	✓	✓	✓	✓					✓				6
	Payload (e.g. Air Conditioning)		✓	✓												2
Vehicle Configuration	Powertrain	✓	✓	✓		✓				✓			✓			6
	EV or HEV	✓	✓	✓		✓		✓	✓	✓		✓			✓	9
	Series or Parallel Configurations		✓	✓								✓				3
	ZEV Range															0
	Charge Sustaining or Charge Depleting			✓												1
	Chassis Systems	✓														1
Vehicle Dynamics	Vehicle Forces				✓		✓									2
	Power and Torque	✓			✓				✓					✓		4
	Vehicle Weights and Capacities				✓									✓		2
Vehicle Performance	Maximum Speed				✓											1
	Acceleration and Deceleration Conditions		✓	✓	✓		✓									4
	Range				✓											1
	Gradability															0
	Fuel Economy (mpg)		✓	✓	✓	✓	✓	✓				✓			✓	8
	Emissions (e.g. CO2, Nox, etc.)		✓	✓		✓		✓				✓			✓	6
	Dynamometer								✓							1
Journey and Driver Data	Drive Cycles (Peak, Cruise and Average Powers)		✓	✓		✓			✓						✓	5
	Prediction of Control Actions on Components of the Drivetrain	✓	✓	✓												3
	Human Response					✓										1
Transmission Data	Transmission Modelling (e.g. CVT)		✓	✓		✓	✓							✓	✓	6
	Differential and Number of Gears	✓				✓			✓					✓		4
	Default Efficiency	✓										✓				2
ICE Information	Basic ICE Choice	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	13
	Alternative APUs (Fuel-cell, Diesel Engine, etc.)	✓											✓			2
	Alternative Fuels (e.g. Hydrogen, CNG, etc.)							✓								1
	ICE Scaling			✓	✓											2
	ICE On-off Control and Modelling	✓	✓	✓					✓					✓		5

	Idle Stop Feature		✓	✓												2
	Hydraulics	✓						✓					✓			3
Electric Motor Information	Basic Electric Motor Choice	✓	✓	✓						✓		✓			✓	6
	Alternative Electric Motor Technologies (e.g. Switched Reluctance, AC Induction, etc.)	✓		✓												2
	Motor Control and Torque Prediction		✓	✓					✓				✓			4
	Electric Motor Assist		✓	✓								✓				3
Battery Information	Basic Battery Choice	✓	✓	✓					✓						✓	5
	Alternative Battery Technologies (e.g. Lead acid, Nickel Metal Hydride, etc.)		✓	✓					✓							3
	Maximum Power															0
	Capacity		✓	✓												2
	State-of-Charge (SOC)		✓	✓												2
	Discharge		✓	✓												2
	Advanced Storage Technologies (Ultra-capacitors, Flywheels, 42-V etc.)		✓	✓				✓		✓						4
Wheel and Tyre Information	Wheel and Tyre Modelling	✓	✓	✓	✓		✓		✓					✓		7
	Mass			✓	✓		✓		✓							4
	Gyration Radius		✓		✓		✓									3
	Rolling Radius/Inertia		✓	✓	✓		✓		✓					✓		6
	Rolling Resistance Coefficient		✓	✓	✓		✓		✓							5
Energy Considerations	Efficiency						✓					✓				2
	Energy and Power Densities														✓	1
	Levels of Regenerative Braking		✓	✓					✓							3
Control Parameter Strategies	Scalable Control Strategy		✓	✓		✓										3
	Sensitivity		✓	✓												2
NVH	Refinement															0
	Sound Quality															0
	System Integration					✓										1
Other Key Realities	Manufacturability															0
	Price and Availability															0
	Maintainability															0
	Safety															0
Modelling Package Compatibility	Graphical Interface	✓	✓	✓	✓		✓		✓				✓			7
	High Speed Execution		✓	✓	✓										✓	4
	Integration with Other Programs	✓	✓	✓	✓		✓			✓			✓			7
	Matlab/Simulink	✓	✓	✓	✓	✓				✓		✓		✓		8
	Excel				✓		✓					✓				3

9.3 Repeatability Data from 1st Assessment

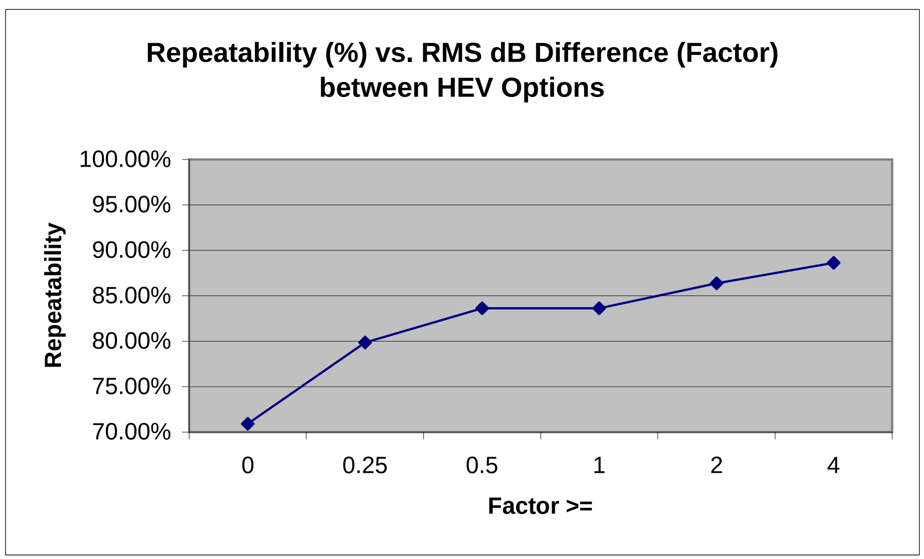
Participant	Repeated Answers?										Repeated Pairs out of 10	Repeatability (%)
	29	30	31	32	33	34	35	36	37	38		
	-10 v -15	No ICE v 0	+15 v +5	-15 v +10	-5 v -10	+5 v No ICE	+10 v +15	-5 v -15	-10 v 0	No ICE v +10		
A	✓	✓	✓	✓	✓	✓	×	×	✓	×	7	70%
B	✓	✓	✓	✓	✓	✓	×	×	✓	✓	8	80%
C	×	✓	✓	✓	✓	✓	✓	×	✓	✓	8	80%
D	×	✓	✓	✓	✓	✓	✓	✓	×	✓	8	80%
E	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	9	90%
F	×	✓	×	×	×	✓	✓	×	✓	✓	5	50%
G	×	✓	✓	✓	×	✓	×	✓	✓	✓	7	70%
H	×	×	✓	✓	×	✓	✓	×	×	✓	5	50%
I	✓	✓	✓	✓	×	✓	✓	×	×	✓	7	70%
J	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	9	90%
K	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	9	90%
L	×	×	✓	✓	×	✓	✓	×	×	×	4	40%
M	✓	✓	✓	✓	×	✓	✓	×	✓	✓	8	80%
N	✓	✓	✓	✓	×	×	✓	✓	✓	×	7	70%
O	✓	✓	✓	✓	×	✓	✓	×	×	✓	7	70%
P	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	9	90%
Q	✓	×	✓	✓	×	✓	×	✓	×	✓	6	60%
R	×	✓	✓	✓	✓	×	✓	✓	×	✓	7	70%
S	✓	×	✓	×	✓	×	✓	✓	✓	✓	7	70%
T	×	✓	×	✓	✓	×	✓	×	✓	✓	6	60%
U	×	✓	✓	×	✓	✓	✓	×	✓	×	6	60%
V	✓	✓	✓	✓	×	✓	✓	×	×	✓	7	70%

	29	30	31	32	33	34	35	36	37	38
Total No. of ✓	13	18	20	19	12	18	17	8	13	18
% Repeated	59.09%	81.82%	90.91%	86.36%	54.55%	81.82%	77.27%	36.36%	59.09%	81.82%
Factor Difference in Overall Loudness	0.03	0.34	5.41	4.12	0.10	1.09	1.82	0.14	0.39	3.77
	29	30	31	32	33	34	35	36	37	38

	Repeated Pairs out of 10	Repeatability (%)
Average	7.09	70.91%

Total No. of Participants **22**

Reapeatability (Full Set)	70.91%	0
Reapeatability >0.25	79.87%	0.25
Reapeatability >0.5	83.64%	0.5
Reapeatability >1	83.64%	1
Reapeatability >2	86.36%	2
Reapeatability >4	88.64%	4



9.4 Recommended Stopping Criteria from 1st Assessment

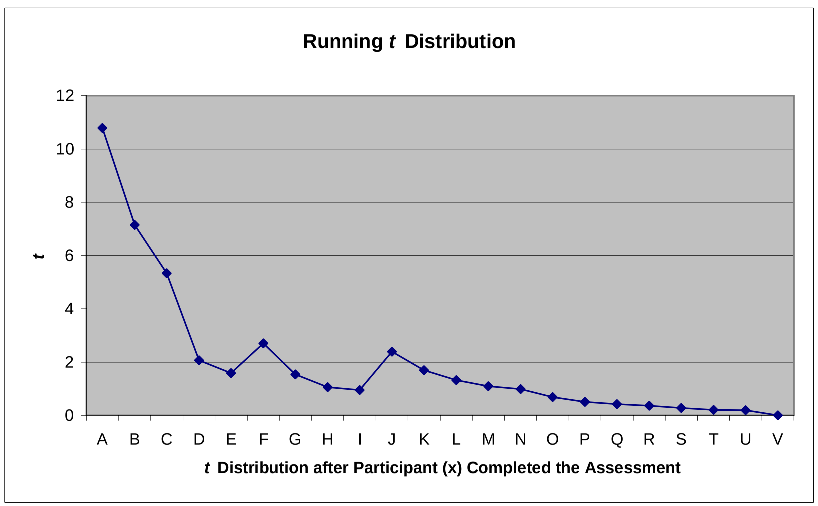
Significant Differences for Stopping Criteria

HEV Option	Running Merit Score																					
	After A	After B	After C	After D	After E	After F	After G	After H	After I	After J	After K	After L	After M	After N	After O	After P	After Q	After R	After S	After T	After U	After V
A/B ICE -15	0.27	0.11	0.30	0.54	0.82	0.47	0.58	0.70	0.71	0.37	0.35	0.44	0.50	0.46	0.48	0.51	0.55	0.53	0.52	0.57	0.51	0.57
A/B ICE -10	-0.41	-0.24	0.17	0.49	0.52	0.35	0.50	0.58	0.61	0.45	0.49	0.54	0.64	0.64	0.61	0.64	0.68	0.54	0.54	0.55	0.49	0.51
A/B ICE -5	0.14	-0.27	-0.17	-0.06	-0.05	-0.06	0.04	0.21	0.35	0.25	0.33	0.37	0.45	0.43	0.46	0.49	0.50	0.53	0.58	0.59	0.57	0.61
A/B ICE 0	0.27	0.62	0.43	0.34	0.25	0.36	0.38	0.40	0.39	0.30	0.45	0.46	0.42	0.48	0.56	0.55	0.55	0.52	0.49	0.51	0.59	0.57
A/B ICE +5	0.27	0.76	0.47	0.20	0.19	0.24	0.02	-0.07	-0.14	-0.09	-0.10	-0.16	-0.21	-0.11	-0.15	-0.15	-0.14	-0.07	0.00	-0.06	0.02	-0.02
A/B ICE +10	-0.14	0.17	-0.21	-0.54	-0.75	-0.64	-0.75	-0.87	-0.97	-0.58	-0.66	-0.71	-0.78	-0.75	-0.81	-0.86	-0.93	-0.86	-0.86	-0.94	-0.89	-0.93
A/B ICE +15	-0.14	-0.24	-0.82	-1.16	-1.41	-0.93	-1.08	-1.23	-1.36	-0.92	-1.03	-1.13	-1.22	-1.30	-1.38	-1.44	-1.48	-1.45	-1.51	-1.48	-1.53	-1.58
A/B No ICE	-0.27	-0.90	-0.17	0.20	0.43	0.22	0.31	0.28	0.41	0.21	0.18	0.18	0.19	0.16	0.21	0.26	0.28	0.26	0.24	0.26	0.25	0.26

HEV Option	Difference between (x) and V																					
	Diff. A - V	Diff. B - V	Diff. C - V	Diff. D - V	Diff. E - V	Diff. F - V	Diff. G - V	Diff. H - V	Diff. I - V	Diff. J - V	Diff. K - V	Diff. L - V	Diff. M - V	Diff. N - V	Diff. O - V	Diff. P - V	Diff. Q - V	Diff. R - V	Diff. S - V	Diff. T - V	Diff. U - V	Diff. V - V
A/B ICE -15	0.29	0.46	0.27	0.03	0.25	0.10	0.01	0.13	0.14	0.20	0.22	0.13	0.07	0.11	0.09	0.05	0.02	0.04	0.05	0.00	0.06	0
A/B ICE -10	0.93	0.76	0.34	0.03	0.01	0.17	0.02	0.06	0.09	0.07	0.03	0.03	0.12	0.12	0.10	0.13	0.17	0.03	0.03	0.03	0.02	0
A/B ICE -5	0.48	0.89	0.79	0.68	0.66	0.68	0.58	0.41	0.27	0.36	0.29	0.24	0.16	0.18	0.15	0.12	0.11	0.08	0.03	0.03	0.04	0
A/B ICE 0	0.30	0.05	0.14	0.23	0.33	0.21	0.19	0.17	0.18	0.27	0.12	0.12	0.15	0.10	0.01	0.03	0.02	0.06	0.09	0.06	0.01	0
A/B ICE +5	0.29	0.78	0.49	0.22	0.21	0.25	0.04	0.05	0.13	0.07	0.08	0.14	0.19	0.09	0.14	0.13	0.13	0.06	0.02	0.04	0.03	0
A/B ICE +10	0.79	1.10	0.71	0.39	0.18	0.29	0.18	0.06	0.04	0.35	0.26	0.22	0.15	0.17	0.12	0.06	0.01	0.07	0.07	0.01	0.04	0
A/B ICE +15	1.45	1.34	0.76	0.42	0.18	0.65	0.51	0.35	0.22	0.66	0.55	0.45	0.36	0.28	0.21	0.14	0.10	0.13	0.07	0.10	0.05	0
A/B No ICE	0.53	1.15	0.43	0.05	0.18	0.03	0.05	0.02	0.16	0.04	0.08	0.07	0.06	0.10	0.04	0.00	0.02	0.01	0.02	0.01	0.01	0

Statistics Variables	Participants																					
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
d bar	0.631	0.816	0.492	0.256	0.248	0.297	0.197	0.157	0.154	0.253	0.203	0.175	0.158	0.145	0.106	0.083	0.073	0.058	0.047	0.035	0.033	0.000
S.D.	0.275	0.536	0.432	0.582	0.733	0.516	0.603	0.694	0.768	0.496	0.563	0.619	0.677	0.690	0.733	0.768	0.800	0.760	0.776	0.792	0.791	0.821
Variance	0.075	0.287	0.187	0.338	0.538	0.266	0.363	0.482	0.589	0.246	0.317	0.383	0.459	0.475	0.537	0.590	0.641	0.577	0.602	0.627	0.626	0.675
k	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t	**10.784**	**7.144**	**5.332**	**2.066**	**1.586**	**2.704**	**1.533**	1.062	0.943	**2.390**	**1.693**	**1.324**	1.094	0.984	0.679	0.504	0.426	0.357	0.282	0.207	0.193	0.000

From tables t= **1.721**



9.5 Recommended Stopping Criteria (Changed Order) from 1st Assessment

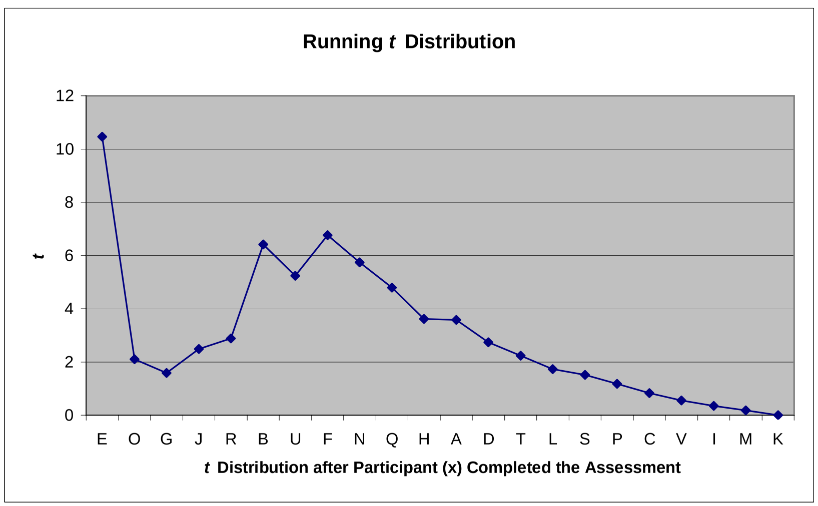
Significant Differences for Stopping Criteria

HEV Option	Running Merit Score																					
	After E	After O	After G	After J	After R	After B	After U	After F	After N	After Q	After H	After A	After D	After T	After L	After S	After P	After C	After V	After I	After M	After K
A/B ICE -15	0.27	0.76	0.99	0.34	0.30	0.13	0.02	-0.14	-0.16	-0.02	0.12	0.17	0.25	0.33	0.41	0.41	0.44	0.47	0.54	0.55	0.59	0.57
A/B ICE -10	0.14	0.26	0.58	0.36	0.00	-0.05	-0.12	-0.15	-0.08	0.02	0.13	0.10	0.20	0.22	0.29	0.31	0.34	0.38	0.41	0.43	0.49	0.51
A/B ICE -5	-0.14	0.14	0.32	0.27	0.40	0.13	0.11	0.05	0.04	0.10	0.23	0.21	0.23	0.27	0.31	0.38	0.41	0.43	0.49	0.54	0.58	0.61
A/B ICE 0	-0.27	0.27	0.32	0.49	0.50	0.55	0.75	0.78	0.86	0.76	0.71	0.71	0.66	0.68	0.66	0.62	0.59	0.56	0.54	0.53	0.50	0.57
A/B ICE +5	0.00	-0.22	-0.58	-0.36	-0.16	0.12	0.32	0.34	0.44	0.42	0.29	0.35	0.26	0.16	0.10	0.16	0.15	0.10	0.06	0.02	-0.01	-0.02
A/B ICE +10	-0.14	-0.79	-1.09	-0.55	-0.40	-0.24	-0.23	-0.21	-0.24	-0.39	-0.48	-0.42	-0.49	-0.61	-0.64	-0.67	-0.72	-0.77	-0.81	-0.85	-0.89	-0.93
A/B ICE +15	-0.27	-1.17	-1.51	-0.96	-0.97	-0.60	-0.80	-0.55	-0.71	-0.81	-0.93	-1.00	-1.10	-1.10	-1.17	-1.24	-1.31	-1.37	-1.43	-1.48	-1.53	-1.58
A/B No ICE	0.41	0.76	0.97	0.41	0.33	-0.04	-0.04	-0.13	-0.16	-0.09	-0.08	-0.12	-0.01	0.04	0.05	0.04	0.09	0.19	0.20	0.27	0.27	0.26

HEV Option	Difference between (x) and V																					
	Diff. E - K	Diff. O - K	Diff. G - K	Diff. J - K	Diff. R - K	Diff. B - K	Diff. U - K	Diff. F - K	Diff. N - K	Diff. Q - K	Diff. H - K	Diff. A - K	Diff. D - K	Diff. T - K	Diff. L - K	Diff. S - K	Diff. P - K	Diff. C - K	Diff. V - K	Diff. I - K	Diff. M - K	Diff. K - K
A/B ICE -15	0.29	0.19	0.42	0.23	0.27	0.44	0.55	0.71	0.73	0.59	0.45	0.40	0.32	0.24	0.16	0.16	0.13	0.10	0.03	0.02	0.02	0
A/B ICE -10	0.38	0.26	0.06	0.15	0.51	0.56	0.64	0.66	0.59	0.49	0.39	0.42	0.31	0.29	0.23	0.20	0.17	0.13	0.10	0.08	0.02	0
A/B ICE -5	0.75	0.48	0.30	0.34	0.22	0.49	0.51	0.56	0.57	0.51	0.38	0.40	0.38	0.35	0.30	0.23	0.20	0.18	0.13	0.08	0.03	0
A/B ICE 0	0.85	0.30	0.26	0.09	0.07	0.02	0.18	0.21	0.29	0.19	0.13	0.14	0.09	0.11	0.09	0.05	0.02	0.02	0.03	0.05	0.07	0
A/B ICE +5	0.02	0.21	0.56	0.35	0.14	0.14	0.33	0.36	0.45	0.44	0.31	0.37	0.27	0.18	0.11	0.17	0.17	0.12	0.08	0.04	0.01	0
A/B ICE +10	0.79	0.13	0.16	0.38	0.53	0.69	0.70	0.72	0.69	0.54	0.45	0.51	0.43	0.32	0.28	0.26	0.21	0.16	0.12	0.07	0.04	0
A/B ICE +15	1.31	0.41	0.08	0.62	0.62	0.98	0.78	1.04	0.88	0.77	0.66	0.58	0.49	0.49	0.41	0.34	0.27	0.21	0.15	0.10	0.05	0
A/B No ICE	0.16	0.51	0.72	0.16	0.07	0.30	0.30	0.39	0.41	0.34	0.33	0.38	0.26	0.22	0.20	0.22	0.17	0.06	0.05	0.01	0.02	0

Statistics Variables	Participants																					
	E	O	G	J	R	B	U	F	N	Q	H	A	D	T	L	S	P	C	V	I	M	K
d bar	0.567	0.310	0.319	0.289	0.305	0.453	0.498	0.579	0.576	0.485	0.387	0.399	0.320	0.273	0.224	0.204	0.167	0.123	0.087	0.056	0.031	0.000
S.D.	0.254	0.694	0.945	0.545	0.496	0.331	0.446	0.402	0.470	0.474	0.502	0.522	0.548	0.572	0.608	0.634	0.666	0.695	0.730	0.761	0.793	0.821
Variance	0.065	0.482	0.892	0.297	0.246	0.110	0.199	0.162	0.221	0.225	0.252	0.273	0.300	0.327	0.370	0.402	0.443	0.483	0.533	0.579	0.629	0.675
k	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t	10.467	2.096	1.584	2.483	2.881	6.420	5.235	6.757	5.746	4.795	3.618	3.585	2.738	2.239	1.727	1.508	1.177	0.829	0.558	0.348	0.184	0.000

From tables t= 1.721



9.6 Difference between Pairs (Overall RMS dB) from 1st Assessment

Difference in Loudness between each Paired Selection

Pair Index	Car A: Assembly Name	Car B: Assembly Name	Difference between Overall RMS dB (High - Low)			Difference in Overall Loudness (High as a percentage of Low)				
			Left	Right	Average	Left	Right	Average	Ratio	Factor
1	A/B ICE -15 (Corrected EM Level)	A/B ICE -10 (Corrected EM Level)	0.17	0.09	0.13	3.99%	2.09%	3.04%	1.03	0.03
2	A/B ICE 0 (Corrected EM Level)	A/B No ICE (Corrected EM Level)	1.19	1.33	1.26	31.52%	35.83%	33.66%	1.34	0.34
3	A/B ICE +5 (Corrected EM Level)	A/B ICE +15 (Corrected EM Level)	7.98	8.16	8.07	528.06%	554.64%	541.21%	6.41	5.41
4	A/B ICE +10 (Corrected EM Level)	A/B ICE -15 (Corrected EM Level)	6.93	7.25	7.09	393.17%	430.88%	411.68%	5.12	4.12
5	A/B ICE -10 (Corrected EM Level)	A/B ICE -5 (Corrected EM Level)	0.40	0.46	0.43	9.65%	11.17%	10.41%	1.10	0.10
6	A/B No ICE (Corrected EM Level)	A/B ICE +5 (Corrected EM Level)	3.07	3.35	3.21	102.77%	116.27%	109.41%	2.09	1.09
7	A/B ICE +15 (Corrected EM Level)	A/B ICE +10 (Corrected EM Level)	4.45	4.54	4.49	178.61%	184.45%	181.51%	2.82	1.82
8	A/B ICE -15 (Corrected EM Level)	A/B ICE -5 (Corrected EM Level)	0.57	0.55	0.56	14.02%	13.50%	13.76%	1.14	0.14
9	A/B ICE 0 (Corrected EM Level)	A/B ICE -10 (Corrected EM Level)	1.35	1.52	1.44	36.46%	41.91%	39.16%	1.39	0.39
10	A/B ICE +10 (Corrected EM Level)	A/B No ICE (Corrected EM Level)	6.60	6.97	6.79	357.09%	397.74%	376.98%	4.77	3.77
11	A/B ICE +15 (Corrected EM Level)	A/B ICE -15 (Corrected EM Level)	11.38	11.79	11.59	1274.04%	1410.08%	1340.46%	14.40	13.40
12	A/B ICE -5 (Corrected EM Level)	A/B ICE 0 (Corrected EM Level)	0.95	1.06	1.01	24.45%	27.64%	26.04%	1.26	0.26
13	A/B ICE -10 (Corrected EM Level)	A/B ICE +5 (Corrected EM Level)	3.23	3.54	3.39	110.38%	125.94%	118.02%	2.18	1.18
14	A/B No ICE (Corrected EM Level)	A/B ICE +15 (Corrected EM Level)	11.05	11.51	11.28	1173.50%	1315.79%	1242.76%	13.43	12.43
15	A/B ICE -15 (Corrected EM Level)	A/B ICE 0 (Corrected EM Level)	1.52	1.61	1.57	41.91%	44.88%	43.38%	1.43	0.43
16	A/B ICE +5 (Corrected EM Level)	A/B ICE -5 (Corrected EM Level)	2.83	3.08	2.96	91.87%	103.24%	97.47%	1.97	0.97
17	A/B ICE +10 (Corrected EM Level)	A/B ICE -10 (Corrected EM Level)	6.76	7.16	6.96	374.24%	420.00%	396.59%	4.97	3.97
18	A/B No ICE (Corrected EM Level)	A/B ICE -15 (Corrected EM Level)	0.33	0.28	0.31	7.89%	6.66%	7.28%	1.07	0.07
19	A/B ICE 0 (Corrected EM Level)	A/B ICE +5 (Corrected EM Level)	1.88	2.02	1.95	54.17%	59.22%	56.68%	1.57	0.57
20	A/B ICE -5 (Corrected EM Level)	A/B ICE +10 (Corrected EM Level)	6.36	6.70	6.53	332.51%	367.74%	349.78%	4.50	3.50
21	A/B ICE -10 (Corrected EM Level)	A/B ICE +15 (Corrected EM Level)	11.21	11.70	11.46	1221.30%	1379.11%	1297.98%	13.98	12.98
22	A/B ICE -15 (Corrected EM Level)	A/B ICE +5 (Corrected EM Level)	3.40	3.63	3.52	118.78%	130.67%	124.65%	2.25	1.25
23	A/B ICE +10 (Corrected EM Level)	A/B ICE 0 (Corrected EM Level)	5.41	5.64	5.53	247.54%	266.44%	256.86%	3.57	2.57
24	A/B ICE +15 (Corrected EM Level)	A/B ICE -5 (Corrected EM Level)	10.81	11.24	11.03	1105.04%	1230.45%	1166.19%	12.66	11.66
25	A/B No ICE (Corrected EM Level)	A/B ICE -10 (Corrected EM Level)	0.16	0.19	0.17	3.75%	4.47%	4.11%	1.04	0.04
26	A/B ICE +5 (Corrected EM Level)	A/B ICE +10 (Corrected EM Level)	3.53	3.62	3.58	125.42%	130.14%	127.77%	2.28	1.28
27	A/B ICE 0 (Corrected EM Level)	A/B ICE +15 (Corrected EM Level)	9.86	10.18	10.02	868.28%	942.32%	904.62%	10.05	9.05
28	A/B ICE -5 (Corrected EM Level)	A/B No ICE (Corrected EM Level)	0.24	0.27	0.26	5.68%	6.41%	6.05%	1.06	0.06
29	A/B ICE -10 (Corrected EM Level)	A/B ICE -15 (Corrected EM Level)	0.17	0.09	0.13	3.99%	2.09%	3.04%	1.03	0.03
30	A/B No ICE (Corrected EM Level)	A/B ICE 0 (Corrected EM Level)	1.19	1.33	1.26	31.52%	35.83%	33.66%	1.34	0.34
31	A/B ICE +15 (Corrected EM Level)	A/B ICE +5 (Corrected EM Level)	7.98	8.16	8.07	528.06%	554.64%	541.21%	6.41	5.41
32	A/B ICE -15 (Corrected EM Level)	A/B ICE +10 (Corrected EM Level)	6.93	7.25	7.09	393.17%	430.88%	411.68%	5.12	4.12
33	A/B ICE -5 (Corrected EM Level)	A/B ICE -10 (Corrected EM Level)	0.40	0.46	0.43	9.65%	11.17%	10.41%	1.10	0.10
34	A/B ICE +5 (Corrected EM Level)	A/B No ICE (Corrected EM Level)	3.07	3.35	3.21	102.77%	116.27%	109.41%	2.09	1.09
35	A/B ICE +10 (Corrected EM Level)	A/B ICE +15 (Corrected EM Level)	4.45	4.54	4.49	178.61%	184.45%	181.51%	2.82	1.82
36	A/B ICE -5 (Corrected EM Level)	A/B ICE -15 (Corrected EM Level)	0.57	0.55	0.56	14.02%	13.50%	13.76%	1.14	0.14
37	A/B ICE -10 (Corrected EM Level)	A/B ICE 0 (Corrected EM Level)	1.35	1.52	1.44	36.46%	41.91%	39.16%	1.39	0.39
38	A/B No ICE (Corrected EM Level)	A/B ICE +10 (Corrected EM Level)	6.60	6.97	6.79	357.09%	397.74%	376.98%	4.77	3.77

ICE -15	87.94	86.95
ICE -10	88.11	87.04
ICE -5	88.51	87.50
ICE 0	89.46	88.56
ICE +5	91.34	90.58
ICE +10	94.87	94.20
ICE +15	99.32	98.74
No ICE	88.27	87.23

9.7 Time and Effort Data from 2nd Assessment

Semantic	Participant					
	C					
	Running Time (s)	Time for Action (s)	Action	Car No.	Value	Times Played
Refinement	0	0	Select Word Pair			
	14	14	Select Car	Car 1		1
	25	11	Rating	Car 1	6.5	
	26	1	Select Car	Car 2		1
	30	5	Rating	Car 2	2	
	39	9	Select Car	Car 3		1
	44	6	Rating	Car 3	7	
	48	3	Select Car	Car 4		1
	52	4	Rating	Car 4	6.5	
	56	4	Select Car	Car 5		1
	58	2	Rating	Car 5	8	
	65	7	Select Car	Car 6		1
	68	2	Rating	Car 6	2	
	74	6	Select Car	Car 7		1
	77	2	Rating	Car 7	8.5	
	83	6	Select Car	Car 8		1
	85	3	Rating	Car 8	8.5	
	92	6	Select Car	Car 9		1
	99	7	Rating	Car 9	4.5	
	102	4	Select Car	Car 6		2
	111	9	Select Car	Car 2		2
	120	9	Select Car	Car 6		3
	128	9	Select Car	Car 2		3
	136	8	Select Car	Car 6		4
	138	1	Rating	Car 6	1.5	
	145	7	Select Car	Car 9		2
	154	10	Rating	Car 9	5	
	155	1	Select Car	Car 4		2
	164	9	Select Car	Car 1		2
	173	9	Rating	Car 1	7	
	174	1	Select Car	Car 3		2
	182	9	Select Car	Car 1		3
	191	9	Select Car	Car 5		2
	200	9	Select Car	Car 8		2
	209	8	Select Car	Car 7		2
			⇩			

Powerfulness	218	9	Select Word Pair			
	226	8	Select Car	Car 1		1
	233	8	Rating	Car 1	3	
	234	1	Select Car	Car 2		1
	240	6	Rating	Car 2	4	
	243	3	Select Car	Car 3		1
	249	6	Rating	Car 3	2.5	
	251	2	Select Car	Car 4		1
	255	4	Rating	Car 4	1	
	260	5	Select Car	Car 5		1
	267	7	Rating	Car 5	0.5	
	269	2	Select Car	Car 6		1
	272	3	Rating	Car 6	4	
	277	6	Select Car	Car 7		1
	280	3	Rating	Car 7	1.5	
	286	6	Select Car	Car 8		1
	288	2	Rating	Car 8	1.5	
	295	7	Select Car	Car 9		1
	304	9	Rating	Car 9	5	
	305	1	Rating	Car 9	5.5	
	308	3	Select Car	Car 9		2
	317	9	Select Car	Car 2		2
	325	9	Select Car	Car 9		3
	332	7	Rating	Car 9	4.5	
	334	2	Select Car	Car 2		3
	335	2	Rating	Car 2	5	
	342	7	Select Car	Car 6		2
	344	2	Rating	Car 6	5	
	351	7	Select Car	Car 1		2
	359	8	Select Car	Car 9		4
	367	8	Select Car	Car 1		3
	369	2	Rating	Car 1	4.5	
	371	2	Rating	Car 1	4	
	376	5	Select Car	Car 9		5
	377	1	Rating	Car 9	4	
	384	7	Select Car	Car 3		2
	393	9	Select Car	Car 7		2
	402	9	Select Car	Car 8		2
	410	8	Select Car	Car 4		2
	418	8	Select Car	Car 8		3
	427	8	Select Car	Car 4		3
	429	2	Rating	Car 4	2	
	435	6	Select Car	Car 7		3
	444	8	Select Car	Car 5		2
			⇩			

Appeal	453	9	Select Word Pair			
	455	3	Select Car	Car 9		1
	463	8	Rating	Car 9	7.5	
	464	1	Select Car	Car 2		1
	466	2	Rating	Car 2	2	
	473	7	Select Car	Car 6		1
	477	4	Rating	Car 6	2	
	482	5	Select Car	Car 1		1
	486	4	Rating	Car 1	6.5	
	491	5	Select Car	Car 3		1
	499	8	Rating	Car 3	7	
	500	1	Select Car	Car 7		1
	508	8	Select Car	Car 8		1
	516	8	Select Car	Car 7		2
	525	8	Select Car	Car 8		2
	534	9	Select Car	Car 4		1
	536	3	Rating	Car 4	4	
	542	6	Select Car	Car 5		1
	549	7	Rating	Car 5	4.5	
	553	4	Select Car	Car 6		2
	558	5	Rating	Car 6	1	
	561	4	Select Car	Car 2		2
	568	6	Rating	Car 2	1.5	
	570	2	Select Car	Car 4		2
	578	8	Select Car	Car 5		2
	586	8	Select Car	Car 8		3
	595	9	Select Car	Car 7		3
	604	9	Select Car	Car 1		2
	612	8	Select Car	Car 3		2
	620	8	Select Car	Car 9		2
	640	19	Save & Exit			
Average		5.8				
Total		639.6				

Table 9.1 Time and Effort Data

9.8 Assessment Results from 2nd Assessment

Evaluation Type	Semantic Differential
Test Name	Test 2 (Varying Control Strategy)
Juror ID	J0001 - J0022
Number of Cars	9
Number of Word Pairs	3

Word Pair Number	1	**Harsh**	**Refined**

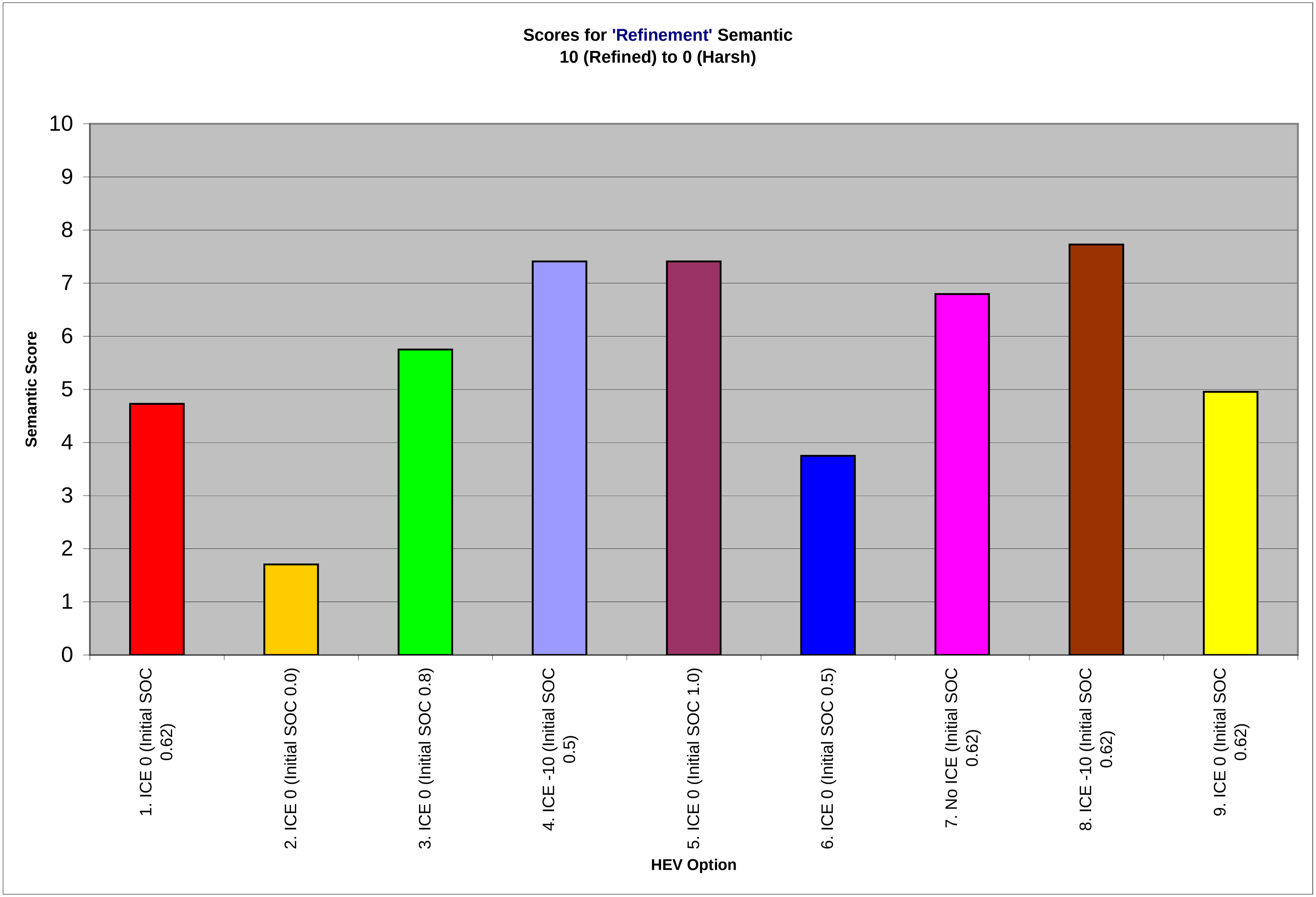
Car Assembly Name	**Button Text**	**Slider Value**
1. ICE 0 (Initial SOC 0.62)	Car 1	4.7
2. ICE 0 (Initial SOC 0.0)	Car 2	1.7
3. ICE 0 (Initial SOC 0.8)	Car 3	5.8
4. ICE -10 (Initial SOC 0.5)	Car 4	7.4
5. ICE 0 (Initial SOC 1.0)	Car 5	7.4
6. ICE 0 (Initial SOC 0.5)	Car 6	3.8
7. No ICE (Initial SOC 0.62)	Car 7	6.8
8. ICE -10 (Initial SOC 0.62)	Car 8	7.7
9. ICE 0 (Initial SOC 0.62)	Car 9	5.0

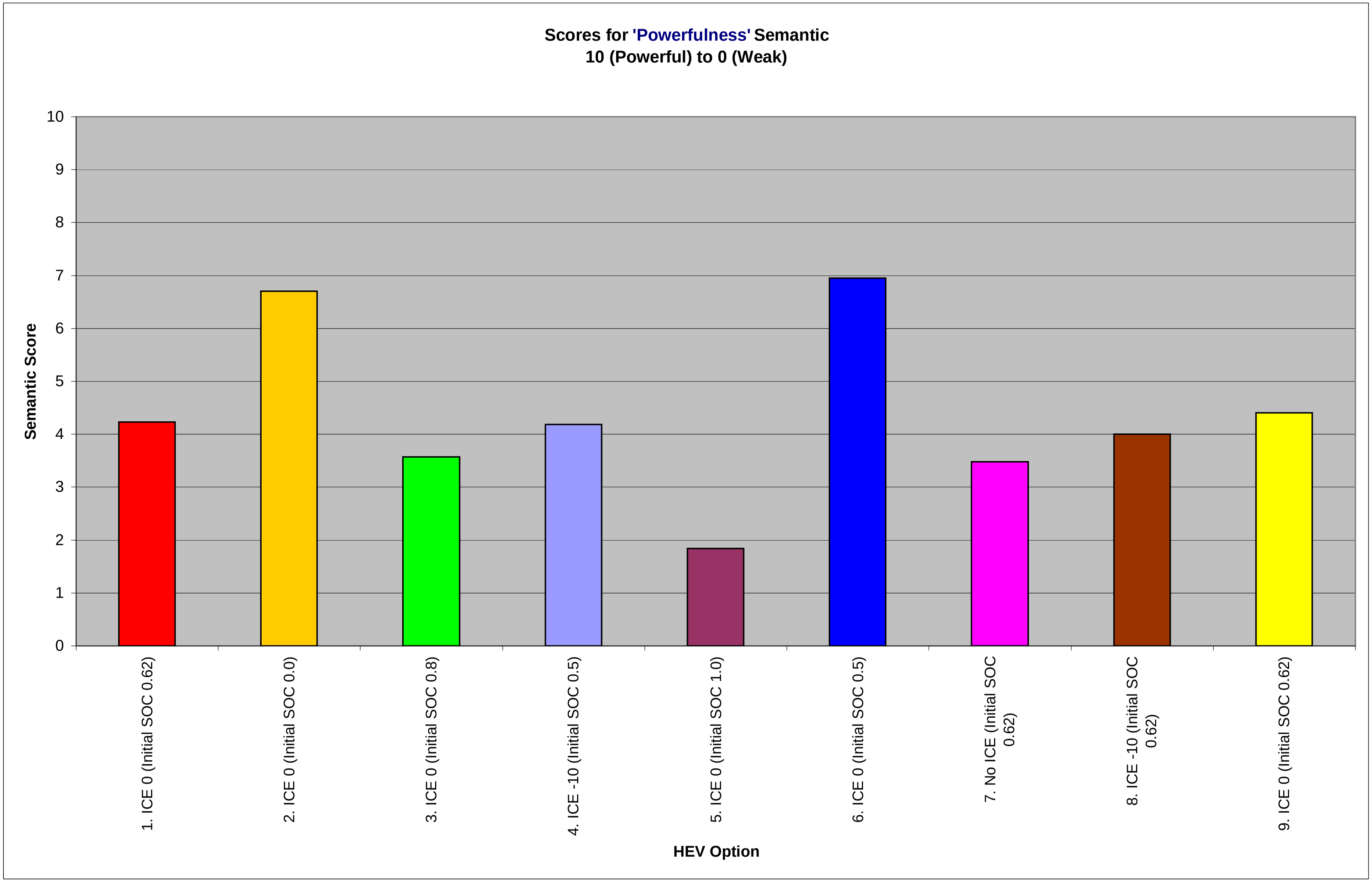
Word Pair Number	2	**Weak**	**Powerful**

Car Assembly Name	**Button Text**	**Slider Value**
1. ICE 0 (Initial SOC 0.62)	Car 1	4.2
2. ICE 0 (Initial SOC 0.0)	Car 2	6.7
3. ICE 0 (Initial SOC 0.8)	Car 3	3.6
4. ICE -10 (Initial SOC 0.5)	Car 4	4.2
5. ICE 0 (Initial SOC 1.0)	Car 5	1.8
6. ICE 0 (Initial SOC 0.5)	Car 6	7.0
7. No ICE (Initial SOC 0.62)	Car 7	3.5
8. ICE -10 (Initial SOC 0.62)	Car 8	4.0
9. ICE 0 (Initial SOC 0.62)	Car 9	4.4

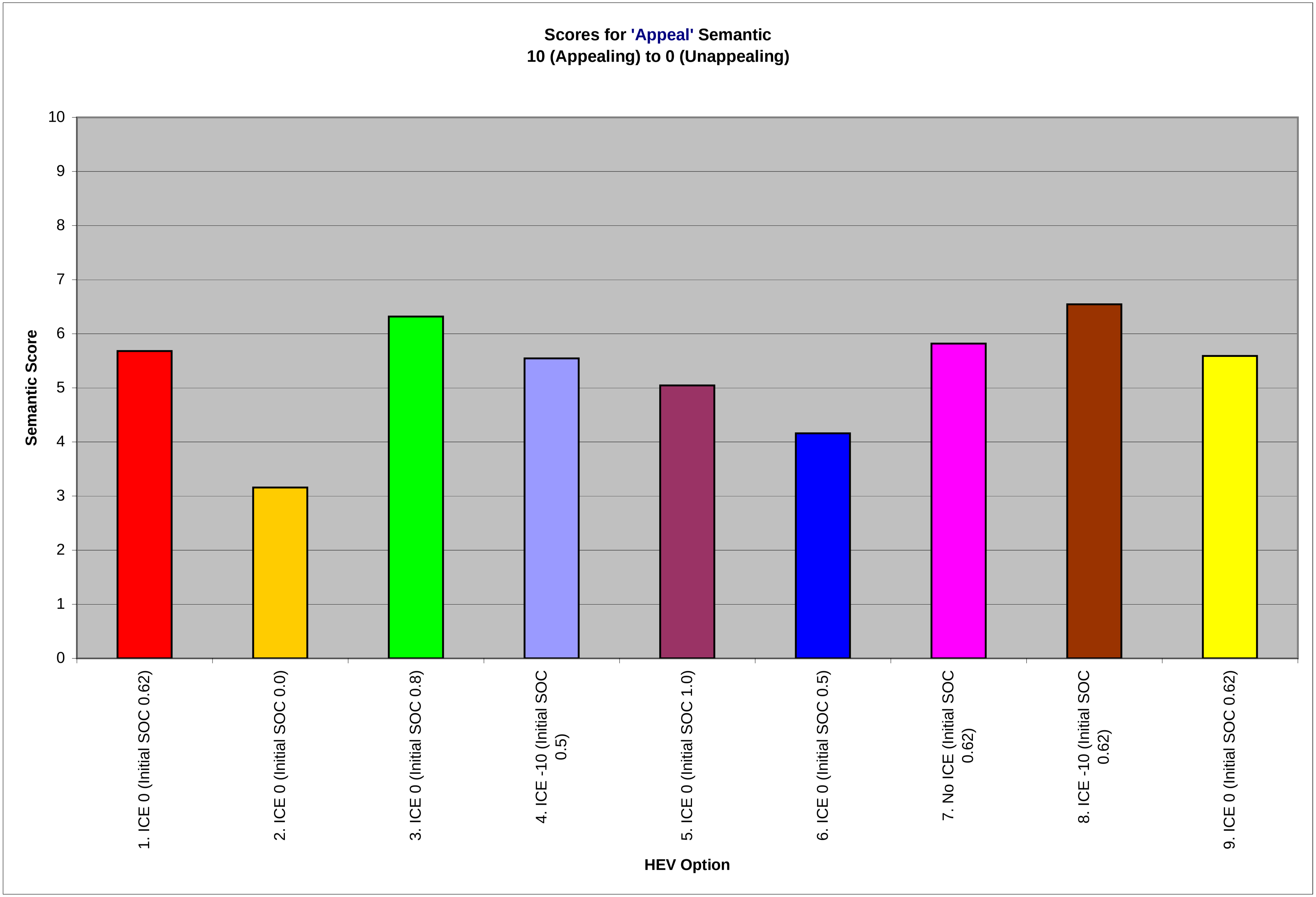
Word Pair Number	3	**Unappealing**	**Appealing**

Car Assembly Name	**Button Text**	**Slider Value**
1. ICE 0 (Initial SOC 0.62)	Car 1	5.7
2. ICE 0 (Initial SOC 0.0)	Car 2	3.2
3. ICE 0 (Initial SOC 0.8)	Car 3	6.3
4. ICE -10 (Initial SOC 0.5)	Car 4	5.5
5. ICE 0 (Initial SOC 1.0)	Car 5	5.0
6. ICE 0 (Initial SOC 0.5)	Car 6	4.2
7. No ICE (Initial SOC 0.62)	Car 7	5.8
8. ICE -10 (Initial SOC 0.62)	Car 8	6.5
9. ICE 0 (Initial SOC 0.62)	Car 9	5.6


Scores for 'Refinement' Semantic
10 (Refined) to 0 (Harsh)
Semantic Score
10
9
8
7
6
5
4
3
2
1
0
1. ICE 0 (Initial SOC 0.62)
2. ICE 0 (Initial SOC 0.0)
3. ICE 0 (Initial SOC 0.8)
4. ICE -10 (Initial SOC 0.5)
5. ICE 0 (Initial SOC 1.0)
6. ICE 0 (Initial SOC 0.5)
7. No ICE (Initial SOC 0.62)
8. ICE -10 (Initial SOC 0.62)
9. ICE 0 (Initial SOC 0.62)
HEV Option



Scores for 'Powerfulness' Semantic
10 (Powerful) to 0 (Weak)
Semantic Score
10
9
8
7
6
5
4
3
2
1
0
1. ICE 0 (Initial SOC 0.62)
2. ICE 0 (Initial SOC 0.0)
3. ICE 0 (Initial SOC 0.8)
4. ICE -10 (Initial SOC 0.5)
5. ICE 0 (Initial SOC 1.0)
6. ICE 0 (Initial SOC 0.5)
7. No ICE (Initial SOC 0.62)
8. ICE -10 (Initial SOC 0.62)
9. ICE 0 (Initial SOC 0.62)
HEV Option



Scores for 'Appeal' Semantic
10 (Appealing) to 0 (Unappealing)
Semantic Score
0
1
2
3
4
5
6
7
8
9
10
1. ICE 0 (Initial SOC 0.62)
2. ICE 0 (Initial SOC 0.0)
3. ICE 0 (Initial SOC 0.8)
4. ICE -10 (Initial SOC 0.5)
5. ICE 0 (Initial SOC 1.0)
6. ICE 0 (Initial SOC 0.5)
7. No ICE (Initial SOC 0.62)
8. ICE -10 (Initial SOC 0.62)
9. ICE 0 (Initial SOC 0.62)
HEV Option

Correlation Coefficient between Semantics

Refinement vs. Powerfulness

-0.81

Refinement vs. Appeal

0.78

Powerfulness vs. Appeal

-0.67

Pearson's Correlation Coefficient between Semantics

Refinement vs. Powerfulness

-0.81

Refinement vs. Appeal

0.78

Powerfulness vs. Appeal

-0.67

Covariance Coefficient between Semantics

Refinement vs. Powerfulness

-2.30

Refinement vs. Appeal

1.48

Powerfulness vs. Appeal

-1.01

9.9 Questionnaire Results from 2nd Assessment

Participant	Pre-Assessment Questionnaire Answers			
	1.1. Brief Description of how decisions were made during the test	1.2. What you felt about the vehicle sounds.	1.3. Any significant differences between the sounds of the vehicle selections?	1.3. If 'yes' or 'unsure', expand upon this.
A	By listening to the car's engine note	The different engine sounds were good for both high and low revs, so would consider buying.	Yes	-
B	Preferred the softer sound with few other noises in the background.	Would consider buying some but not all as some did not sound very nice.	Yes	You could hear some had higher revs and therefore felt faster.
C	For both the assessment of refinement and appeal it was easier to choose between vehicle selections (wider range). Vehicles were lacking in power, therefore ranked closely for powerfulness.	The three vehicles rated the highest for appeal were particularly refined and still had a satisfying character.	Yes	Definitely in terms of refinement and appeal. The drive cycles seemed different in some cases.
D	For the three semantics there was clear difference between the vehicle selections. The vehicles presented were more refined on the whole rather than powerful, which I preferred.	For a number of the vehicle selections the sound was very appealing.	Yes	Some of the vehicle selections appeared faster than others.
E	I found it useful to use the reshuffle button once I had made my initial votes. Initially my votes were very close for certain selections.	The vehicle sounds were quiet yet still had a sense of character.	Yes	Some were louder and less refined than others.
F	I based my decisions on the given semantics. Finding it slightly easier to base my decisions on how appealing the vehicles were.	There was a wide variation and I think there was also a repeated selection within the assessment.	Yes	Some were clearly more appealing than others.
G	The appealing semantic was the easiest to complete as I felt very strongly both for and against a number of the vehicle selections presented.	The more refined vehicles were the most appealing.	Yes	Some vehicle selections were more aggressive and were less appealing.
H	Initially I focused on getting the vehicle selections in rank order then used the reshuffle button to fine tune my votes.	I found the majority of the vehicle selection sounds very appealing.	Yes	There were differences in the level of the engine as the electric motor sound was more evident in some selections.
I	I focused on the visuals provided in order to base my decisions on my perception of the vehicle speed.	Some of the vehicle selections were over faster drive cycles and therefore sounded more powerful.	Yes	The overall sound levels were varied across all selection.
J	I found the semantics self explanatory and based my decisions on the two extreme word pairings.	The more refined the vehicle was the better it felt in terms of comfort.	Yes	Some vehicles were very smooth in operation yet there were others which were too aggressive.
K	The softer sounding vehicle selections were the most appealing.	With some vehicle selections there were periods of big step changes between the sound level. I found this unappealing.	Yes	-
L	I made a vote on each of the 9 selections then used the reshuffle button to replay the selections I originally placed closed to one another.	They were varied yet I preferred the more refined within the selection.	Yes	Some were more aggressive and less appealing than others.
M	-	I would consider buying a vehicle with a number of these sounds.	Yes	There was a wide range for each of the 3 semantics.
N	I listened to the engine sound which was dominant in most of the vehicle selections.	-	Yes	There were clear differences in the levels and separate contributions to the overall vehicle sounds.
O	I focused on the level of the sound as a basis for the refinement and powerfulness semantics.	It was hard to distinguish between certain vehicle selections as they were very similar if not the same in some cases.	Yes	The engine sound level was the most obvious difference between selections.
P	I based how appealing the vehicles were with how smooth the vehicle sound was.	Many were very refined and were very satisfying to listen to.	Yes	Some were too loud and aggressive.
Q	I changed my vote a number of times once I reordered my scores, which I found really useful to compare those which I deemed similar.	On the whole they sounded very good.	Yes	The engine was louder in some cases with was too dominant in some cases.
R	I found the words at each end helpful when making my decisions on each semantic. The easiest screen was the 'appealing' one.	There were more appealing vehicle selections than unappealing.	Yes	The vehicle speed was different in some cases.
S	I listened to each vehicle selection once and then reordered my initial scores at least once each time to refine my choice.	The sounds had character and were generally quite refined, which I liked.	Yes	The overall sound level was different between selections, with clear differences in engine sound in many cases.
T	I scored a vehicle highly if there was a more constant vehicle sound. I didn't like some where the levels changed quite a lot.	Most were pleasant and appealing.	Yes	Some had a greater change of sound, for example the level of the ICE was different in many cases.
U	I used the reshuffle button to revisit initial votes where I scored selections closely.	I think the sounds were different to a conventional vehicle but I still liked the majority of sounds.	Yes	The drive cycle was different for some as the engine speed was faster/louder in some cases.
V	I found the vehicle selections more refined than powerful. Making it easier to score them based on their level of refinement.	Most were refined and I found them more appealing than the more powerful selections.	Yes	There were differences in the overall vehicle sounds but some were very close.

9.10 Questionnaire Results from 3rd Assessment

Questionnaire Results

Participant	Vehicle Option								
	1. ICE 0 (+ Car 1 ICE Sound)	2. Car 2	3. Car 2 + EM (-10)	4. ICE -10	5. Car 1	6. ICE 0 (+ Car 2 ICE Sound)	7. No ICE	8. Car 2 + EM (-2)	9. ICE 0
A	Conventional ICE	HEV	Unsure	EV	HEV	HEV	EV	Conventional ICE	HEV
B	Conventional ICE	Conventional ICE	Unsure	HEV	Conventional ICE	Conventional ICE	HEV	Conventional ICE	Conventional ICE
C	HEV	Unsure	Conventional ICE	HEV	HEV	Conventional ICE	EV	Unsure	HEV
D	Unsure	Conventional ICE	HEV	Unsure	HEV	HEV	EV	HEV	EV
E	Conventional ICE	Conventional ICE	Conventional ICE	HEV	Unsure	Unsure	HEV	Conventional ICE	HEV
F	HEV	Conventional ICE	HEV	Conventional ICE	Conventional ICE	HEV	HEV	HEV	Unsure
G	HEV	Conventional ICE	HEV	EV	Conventional ICE	Conventional ICE	Unsure	Conventional ICE	HEV
H	Conventional ICE	HEV	Conventional ICE	HEV	HEV	Unsure	HEV	Conventional ICE	Unsure
I	Conventional ICE	Conventional ICE	HEV	HEV	Unsure	Unsure	EV	Unsure	EV
J	HEV	Conventional ICE	Conventional ICE	EV	Conventional ICE	Conventional ICE	HEV	Conventional ICE	HEV
K	Conventional ICE	HEV	Conventional ICE	Unsure	HEV	Conventional ICE	HEV	HEV	HEV
L	Conventional ICE	Conventional ICE	Unsure	Conventional ICE	Conventional ICE	HEV	EV	Conventional ICE	HEV
M	Unsure	Conventional ICE	Conventional ICE	HEV	HEV	Conventional ICE	HEV	HEV	EV
N	HEV	Unsure	Conventional ICE	EV	Conventional ICE	HEV	HEV	HEV	Unsure
O	Conventional ICE	Conventional ICE	Unsure	HEV	Conventional ICE	HEV	EV	Conventional ICE	EV
P	HEV	Conventional ICE	Unsure	HEV	Unsure	Unsure	Unsure	Conventional ICE	HEV
Q	HEV	Unsure	Conventional ICE	Unsure	Conventional ICE	Conventional ICE	EV	Unsure	HEV
R	Conventional ICE	Conventional ICE	HEV	HEV	HEV	Conventional ICE	HEV	Conventional ICE	Unsure
S	Unsure	Conventional ICE	Conventional ICE	EV	Conventional ICE	Unsure	HEV	HEV	HEV
T	Conventional ICE	HEV	HEV	HEV	Conventional ICE	Unsure	Unsure	Unsure	Conventional ICE
U	Conventional ICE	Conventional ICE	Conventional ICE	HEV	HEV	HEV	EV	Conventional ICE	EV
V	Conventional ICE	Conventional ICE	HEV	EV	Unsure	Conventional ICE	Unsure	Unsure	HEV

Responses	Responses Given for Each Vehicle Option								
Conventional ICE	12	15	10	2	10	9	0	11	2
HEV	7	4	7	11	8	7	10	6	11
EV	0	0	0	6	0	0	8	0	5
Unsure	3	3	5	3	4	6	4	5	4

Actual Vehicle Technology of each Selection	Vehicle Option								
	1. ICE 0 (+ Car 1 ICE Sound)	2. Car 2	3. Car 2 + EM (-10)	4. ICE -10	5. Car 1	6. ICE 0 (+ Car 2 ICE Sound)	7. No ICE	8. Car 2 + EM (-2)	9. ICE 0
	HEV	Conventional ICE	HEV	HEV	Conventional ICE	HEV	EV	HEV	HEV

9.11 Questionnaire Plots of Responses from 3rd Assessment

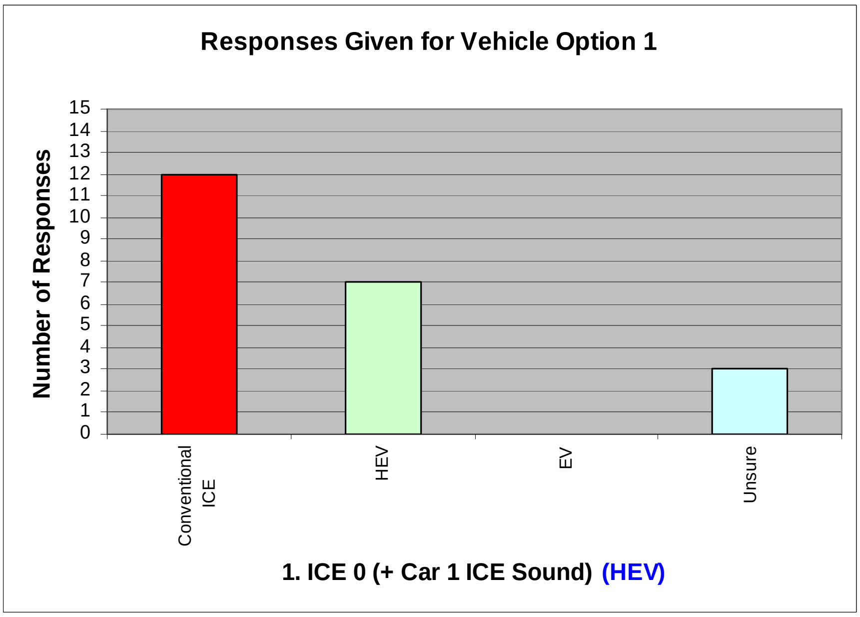


Figure 9.1 Responses Given for Vehicle Option 1

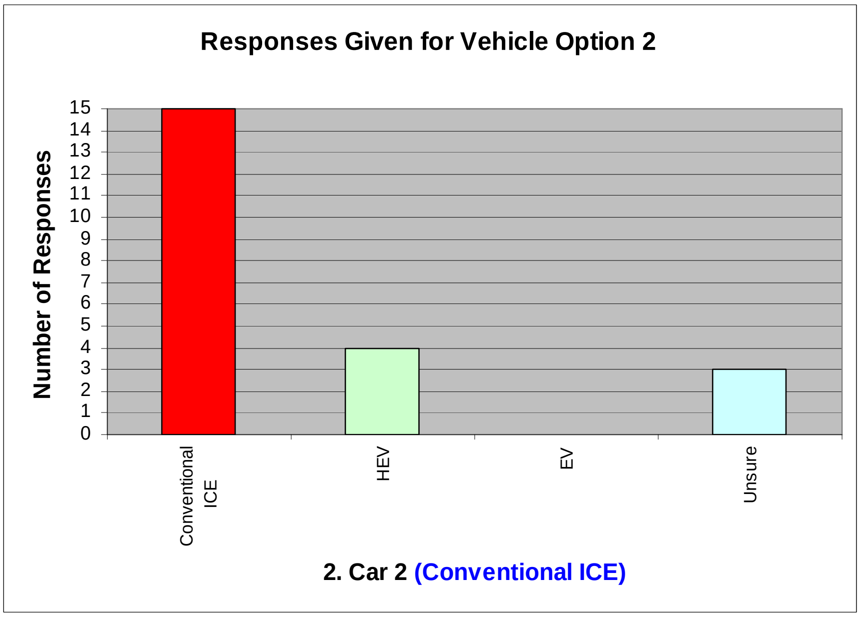


Figure 9.2 Responses Given for Vehicle Option 2

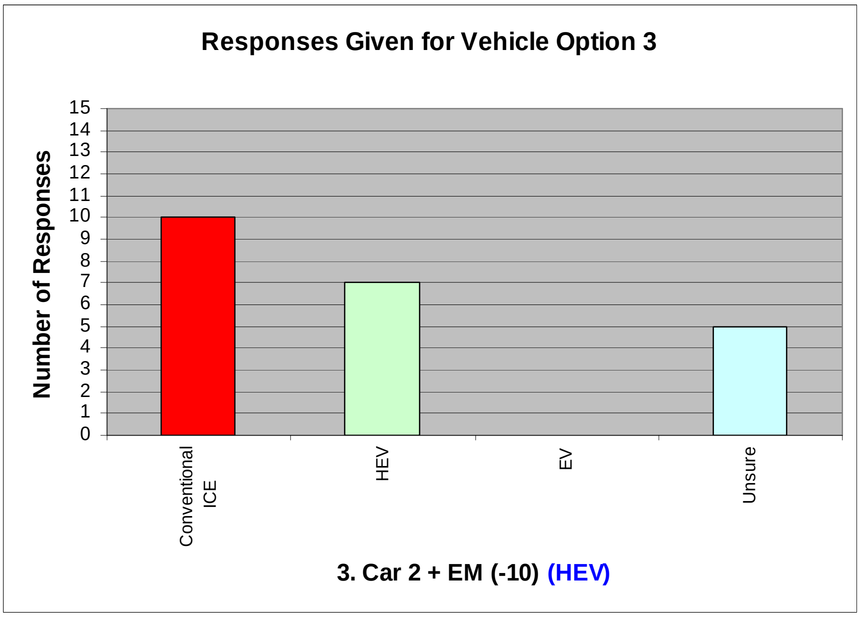


Figure 9.3 Responses Given for Vehicle Option 3

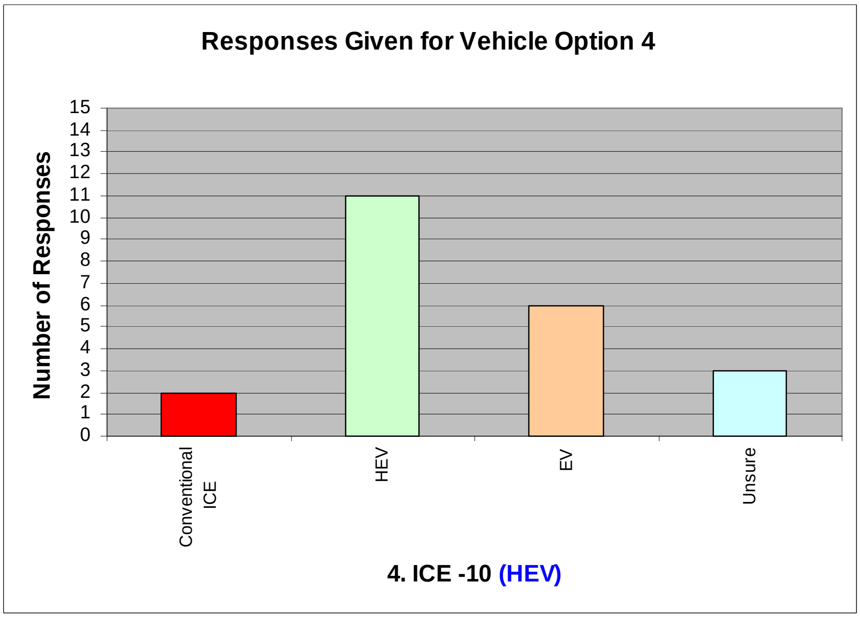


Figure 9.4 Responses Given for Vehicle Option 4

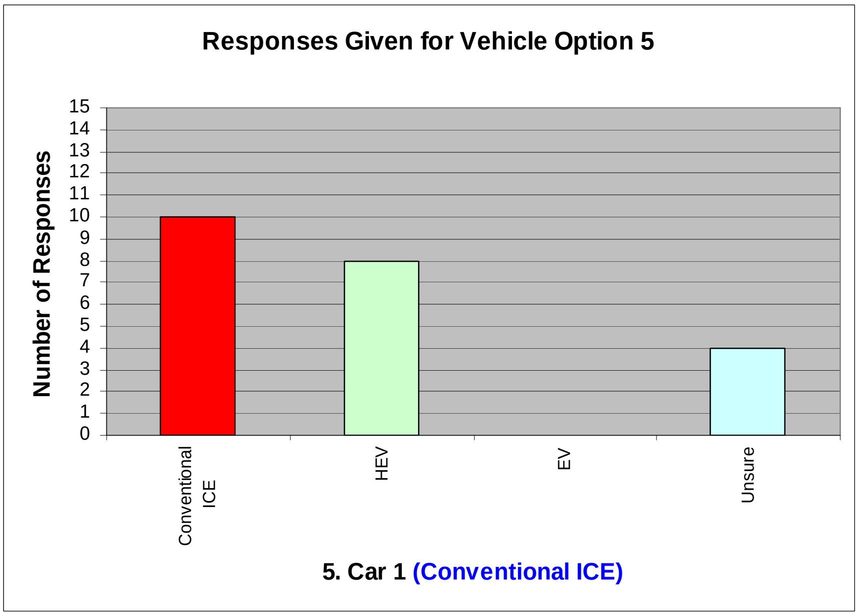


Figure 9.5 Responses Given for Vehicle Option 5

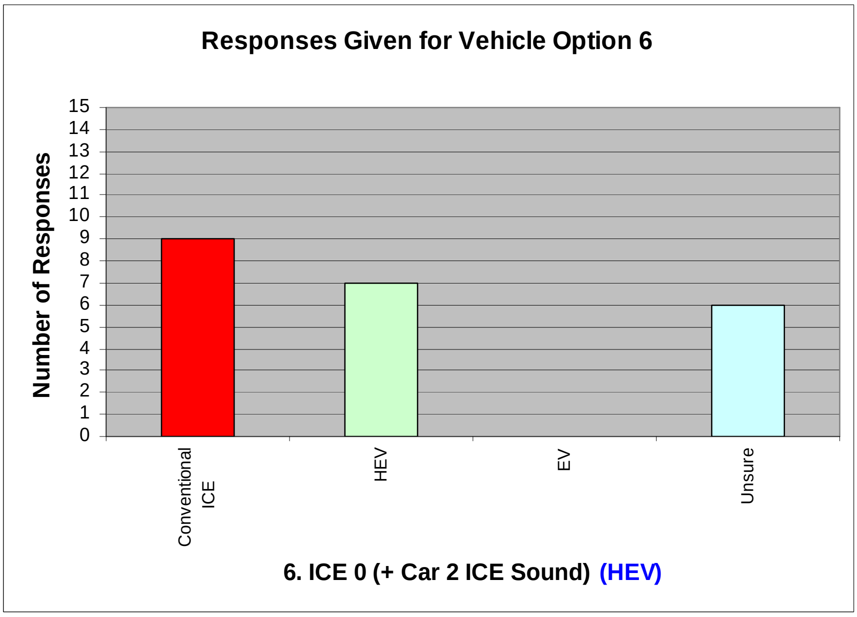


Figure 9.6 Responses Given for Vehicle Option 6

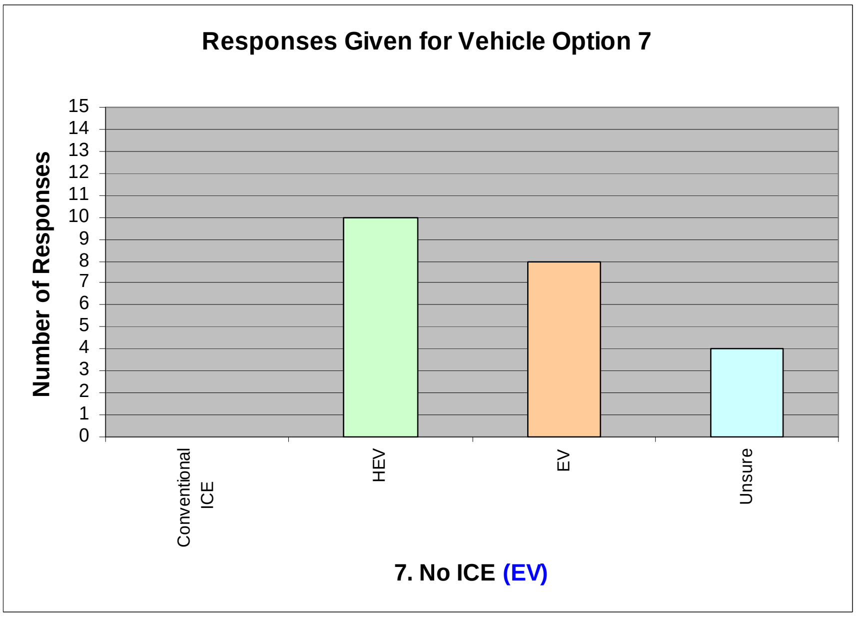


Figure 9.7 Responses Given for Vehicle Option 7

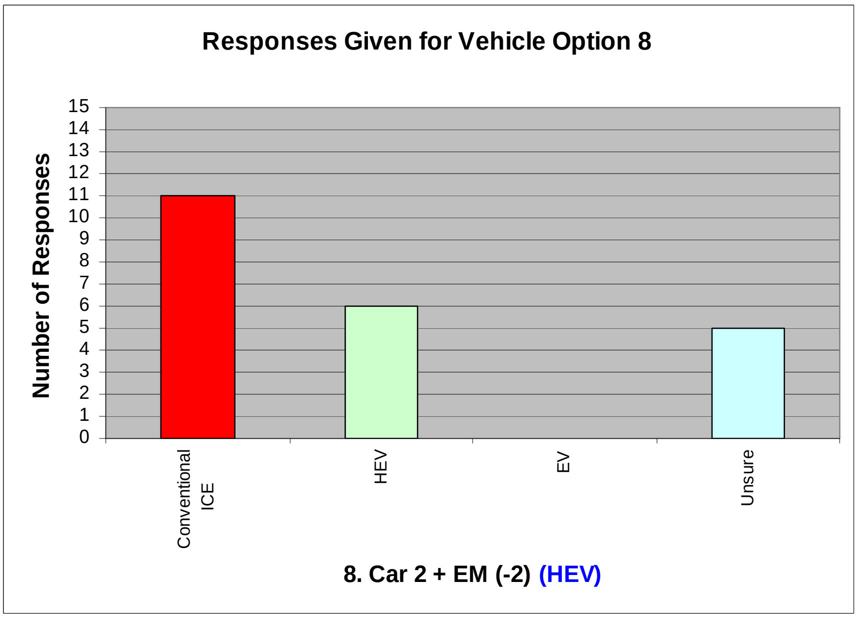


Figure 9.8 Responses Given for Vehicle Option 8

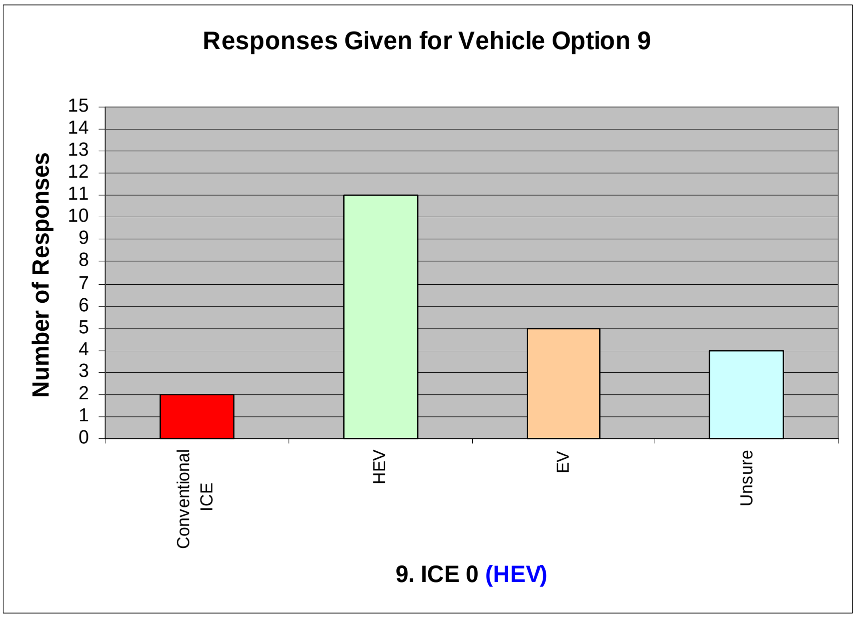


Figure 9.9 Responses Given for Vehicle Option 9

9.12 Process Flow Chart (1) –HEV Model Installation and Validation

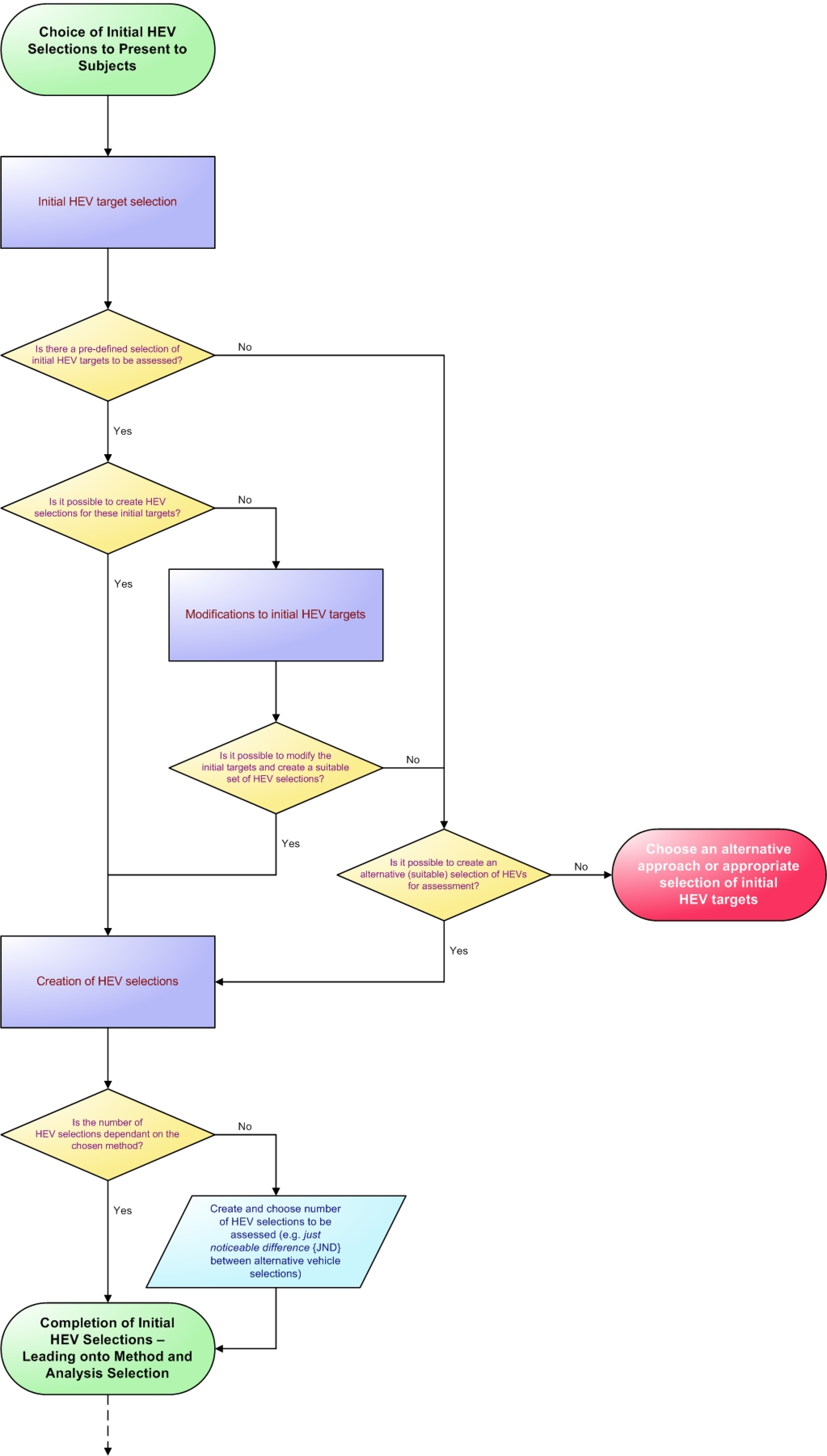
(1) HEV Model Installation and Validation

9.13 Process Flow Chart (1) – Case Study (From 1st Assessment)

(1) Case Study - *Toyota Prius* Model Installation and Validation

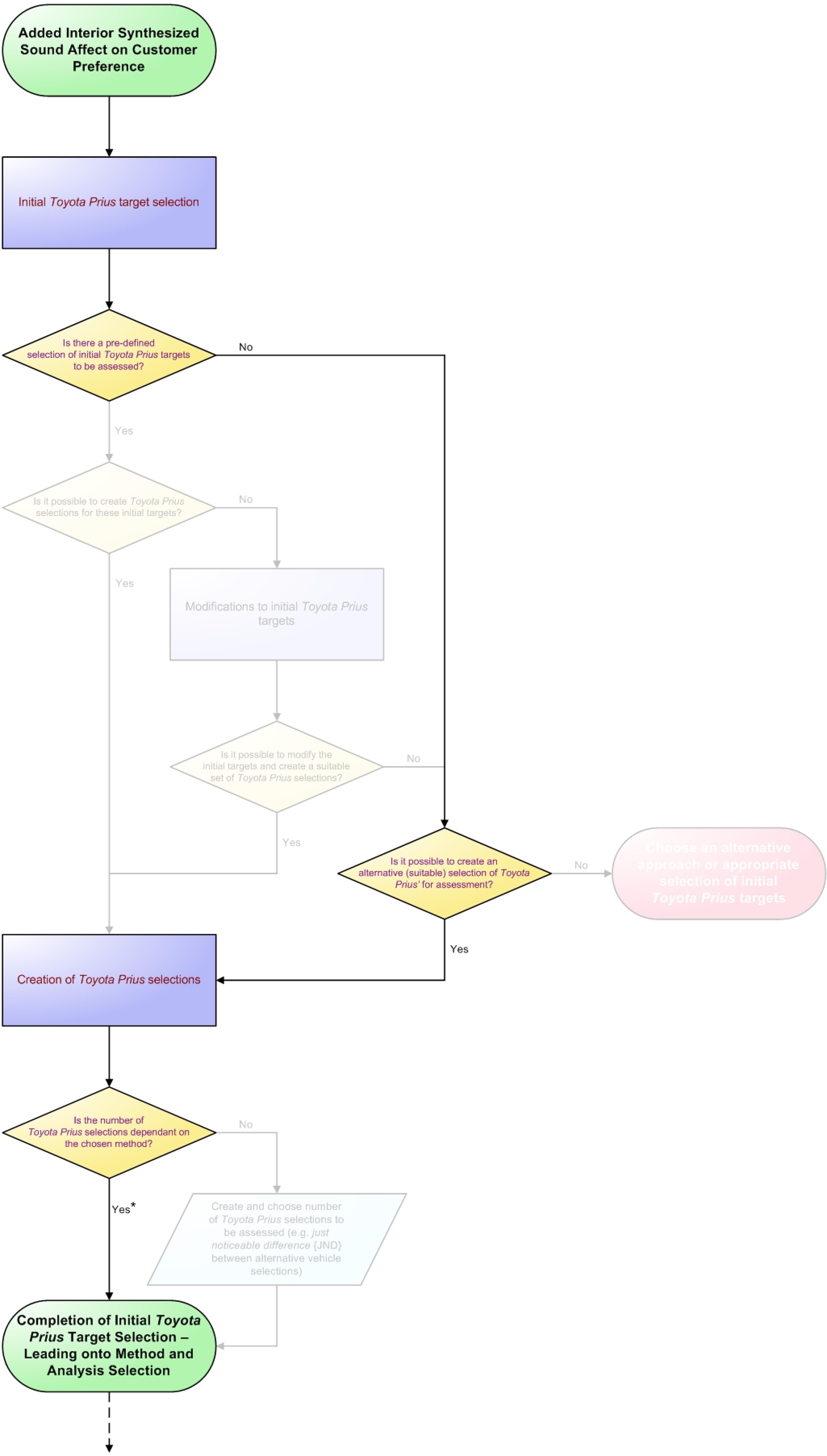
9.14 Process Flow Chart (2) – Choice of Initial HEV Selections

(2) Choice of Initial HEV Selections to Present to Subjects



9.15 Process Flow Chart (2) – Case Study (From 3rd Assessment)

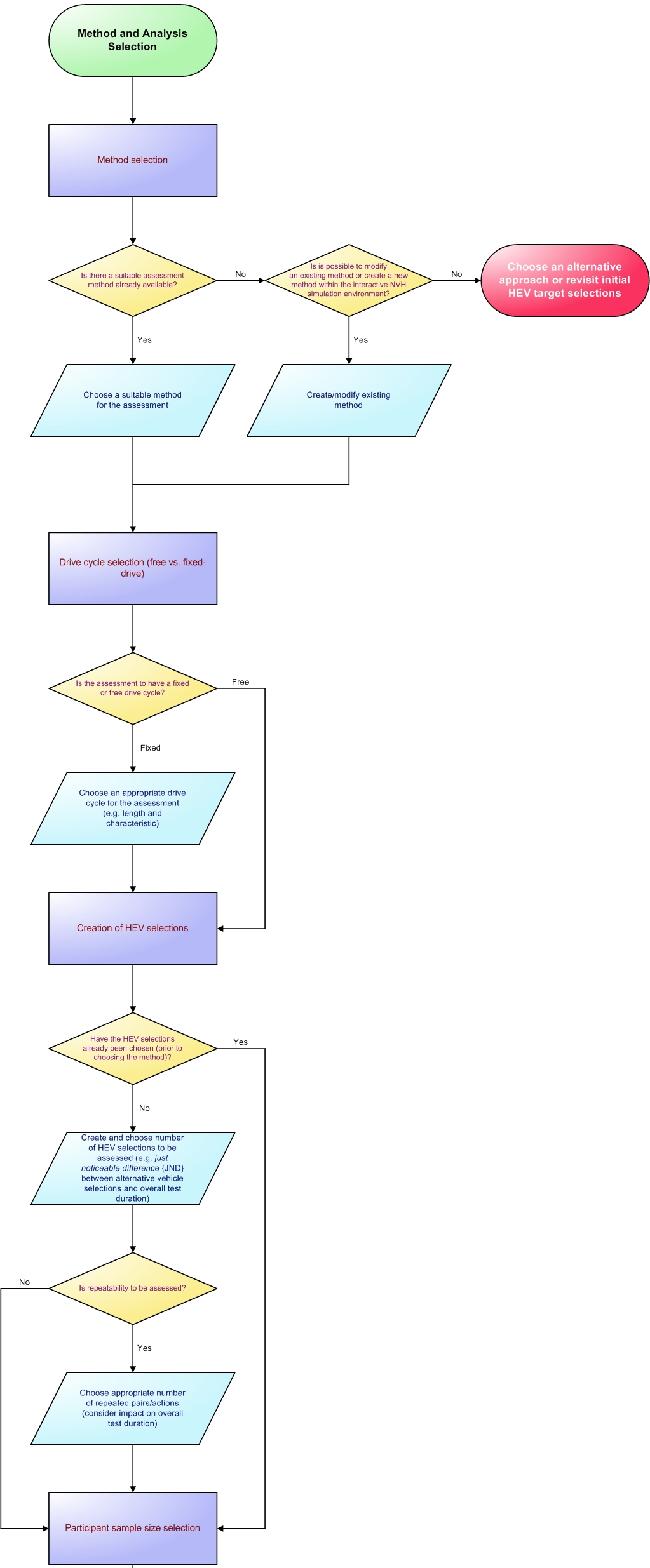
(2) Case Study - Initial *Toyota Prius* Targets for the Assessment of Added Interior Synthesized Sound Affect on Customer Preference



* The choice of the number of *Toyota Prius* selections required was limited to 9 in order to consider a suitable test duration (< 30 mins) for semantic differential evaluation with 3 semantics (As with the previous assessment).

9.16 Process Flow Chart (3) – Method and Analysis Selection

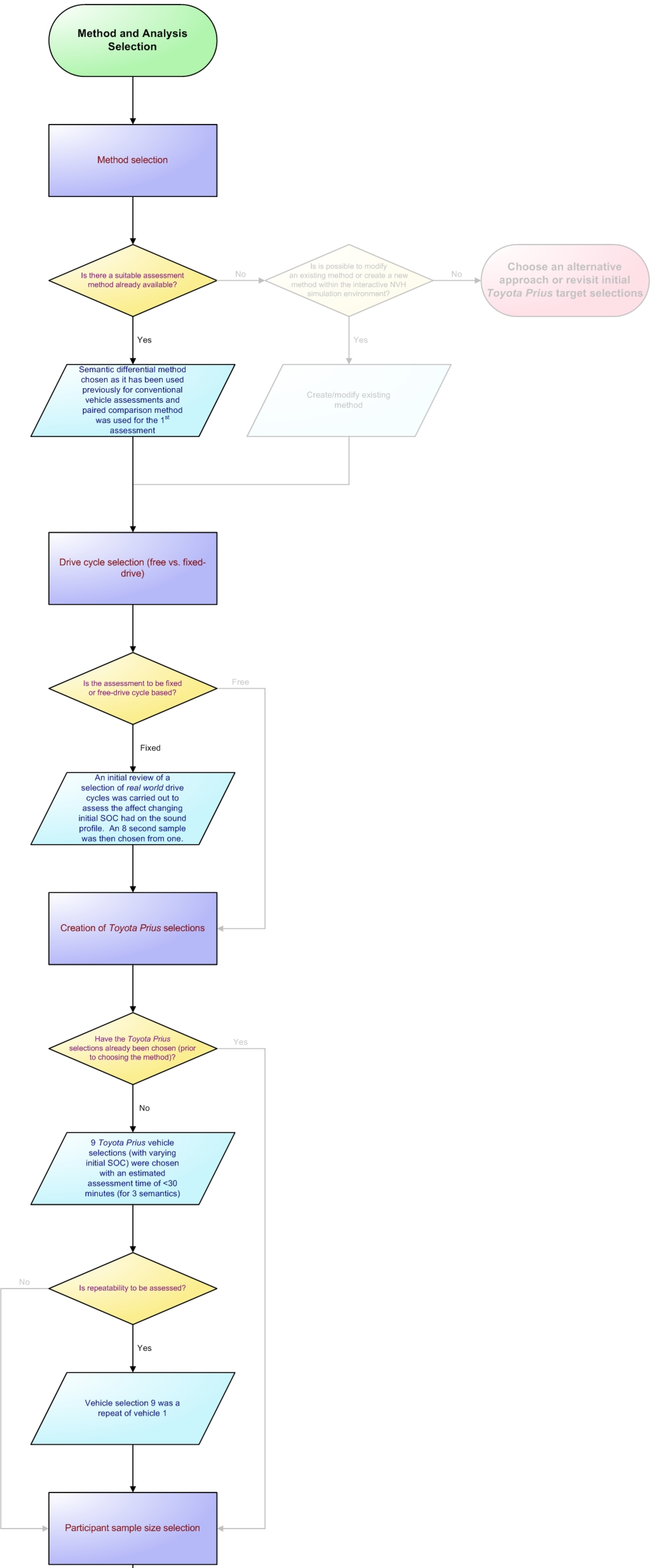
(3) Method and Analysis Selection



Choose appropriate sample size. (e.g. recommended sample size/stopping criteria considerations)
Questionnaire selection/creation
Is there the requirement for a supporting questionnaire?
No
Yes
Create questionnaire which addresses the additional HEV information required from the assessment
Run assessment
Run assessment until chosen sample size or stopping criteria point has been met
Analysis
Is there standard analysis which needs to be carried out?
No
Yes
Analyse assessment with a selection of standard analysis techniques (e.g. repeatability, ANOVA and stopping criteria)
Is there additional analysis which needs to be carried out?
No
Yes
Carry out non-standard analysis (e.g. questionnaire correlation, time and effort of assessment)
HEV target recommendation/selection
Recommendations made in conjunction with other development areas (cost, performance, business) for improved HEV selection

9.17 Process Flow Chart (3) – Case Study (From 2nd Assessment)

(3) Case Study - Method and Analysis Selection

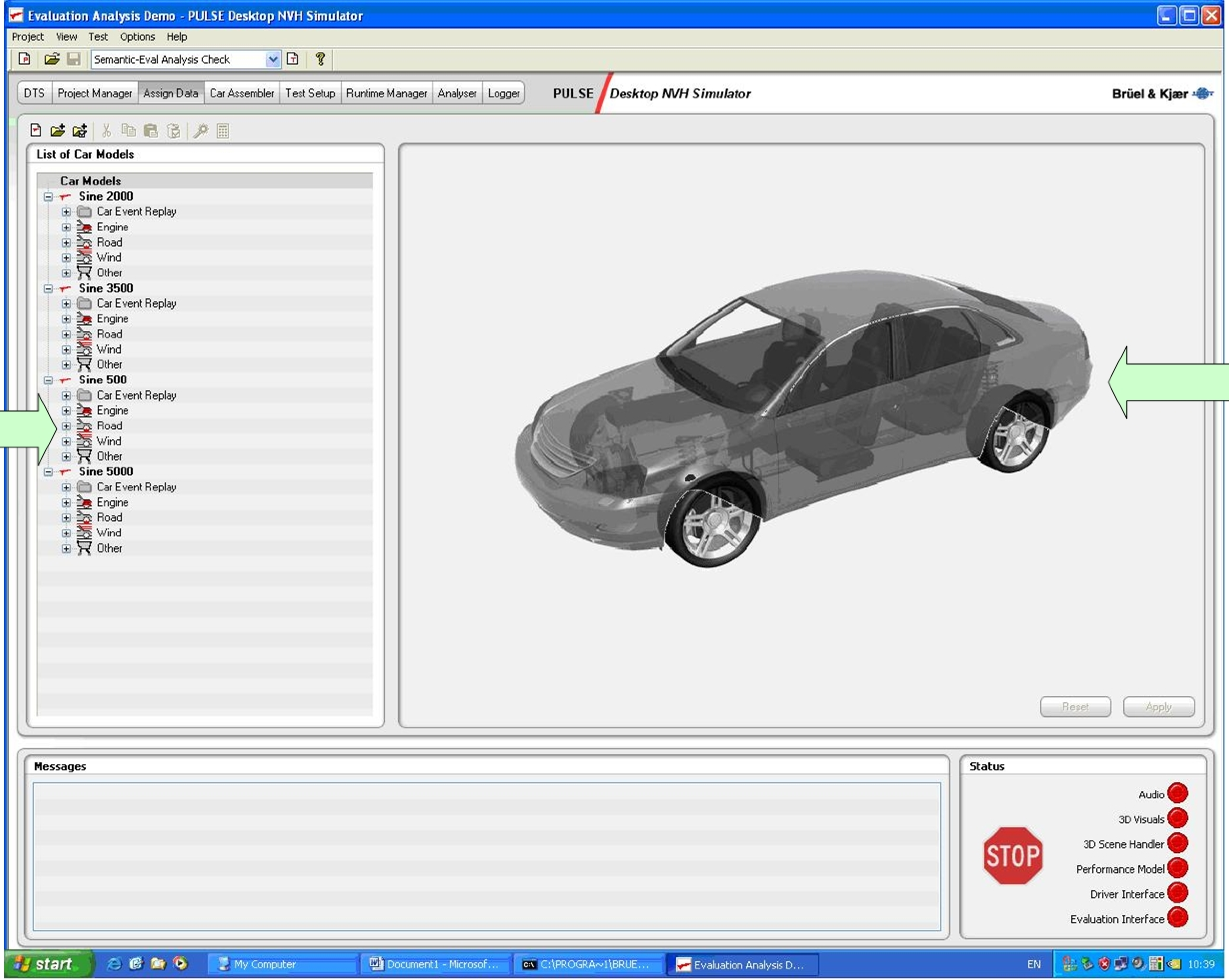



22 participants were chosen as with the 1st assessment
Questionnaire selection/creation
Is there the requirement for a supporting questionnaire?
No
Yes
A post-assessment questionnaire was created to capture more specific details on how decisions were made during the test
Run assessment
The assessment was carried out on a one to one basis and completed for the full set of 22 participants
Analysis
Is there standard analysis which needs to be carried out?
No
Yes
Initial analysis was carried out in the forms of repeatability and correlation of semantic scores
Is there additional analysis which needs to be carried out?
No
Yes
Additional analysis was carried out on an in-depth questionnaire correlation and time and effort of assessment
Toyota Prius target recommendation/ selection
Recommendations were made for a variety of selected target customers (within report)

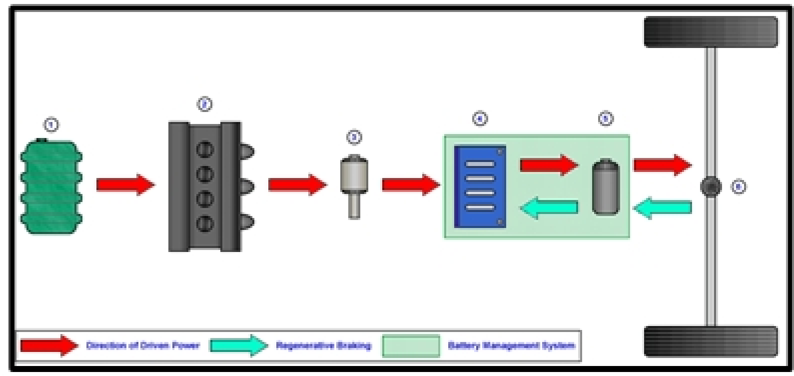
9.18 *Brüel & Kjær* Advertisement for HEV NVH Target Setting

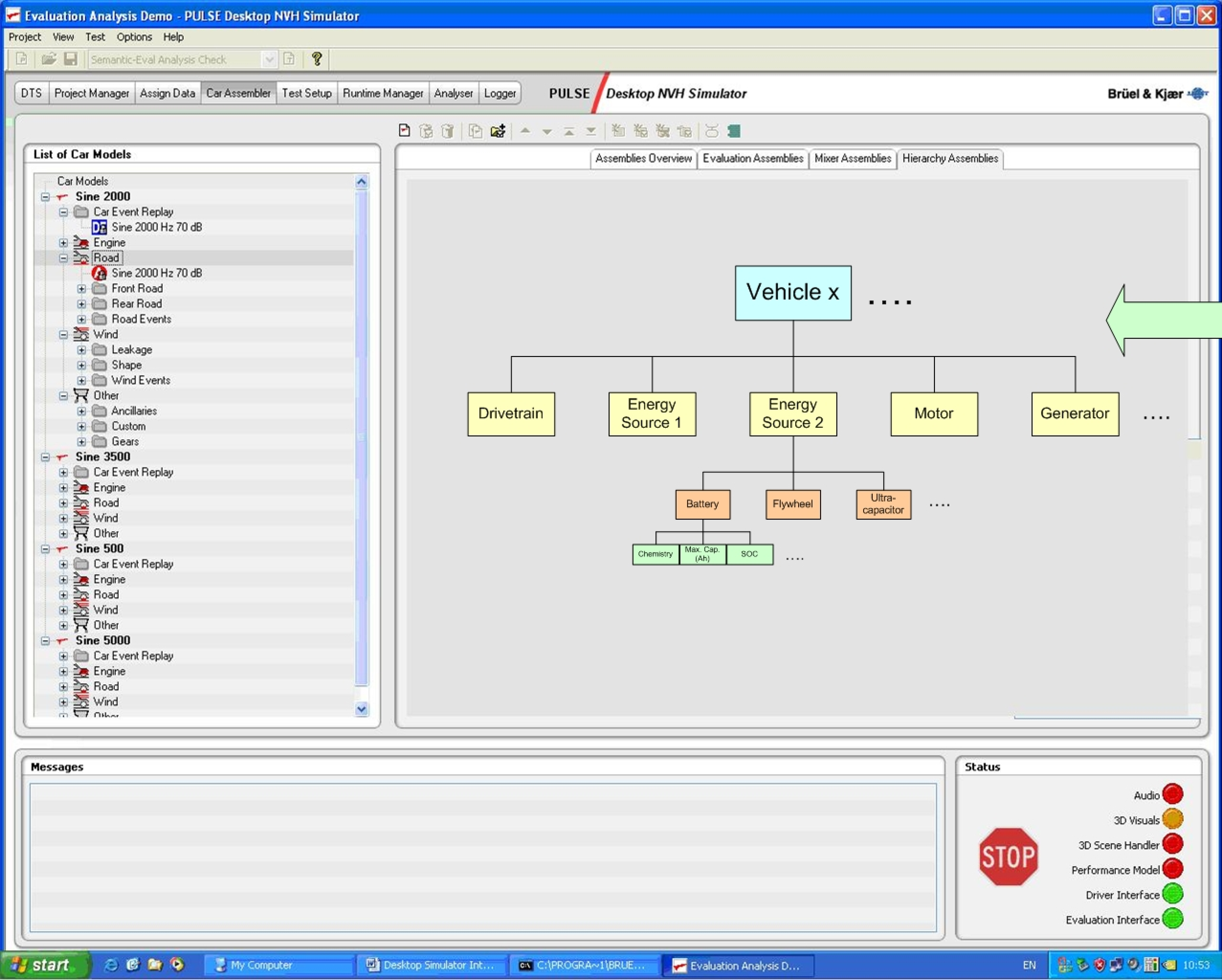
9.19 User Interface Suggestions

New hybrid vehicle additions:
- Drivetrain (Series, Parallel, Split…)
  - Electric motor
  - Generator
- Battery (capacity, SOC levels)

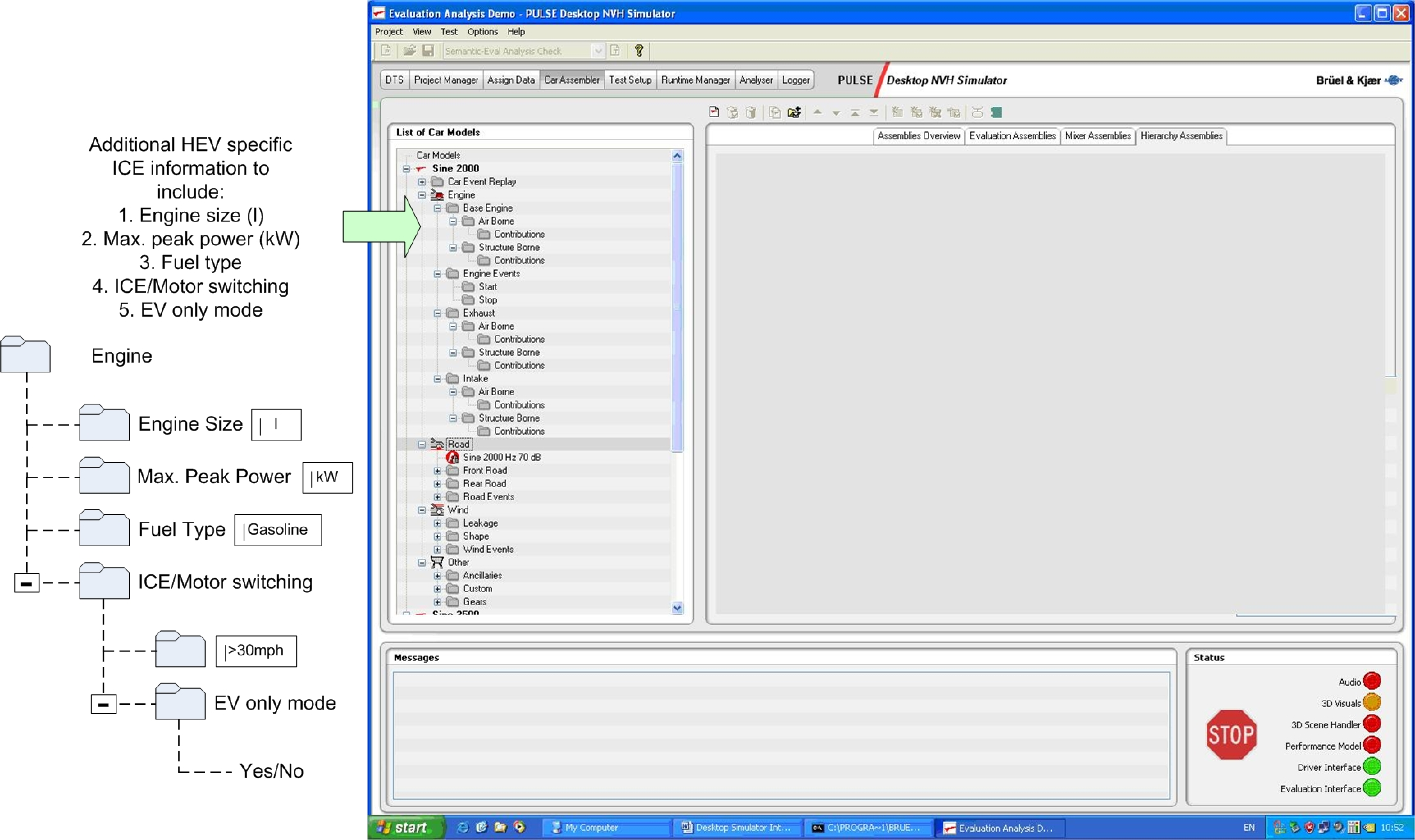


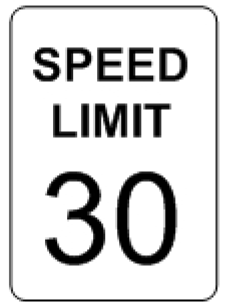
Assign hybrid (*.gif and *.jpeg) images.



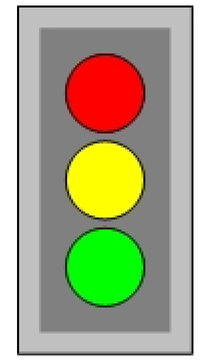


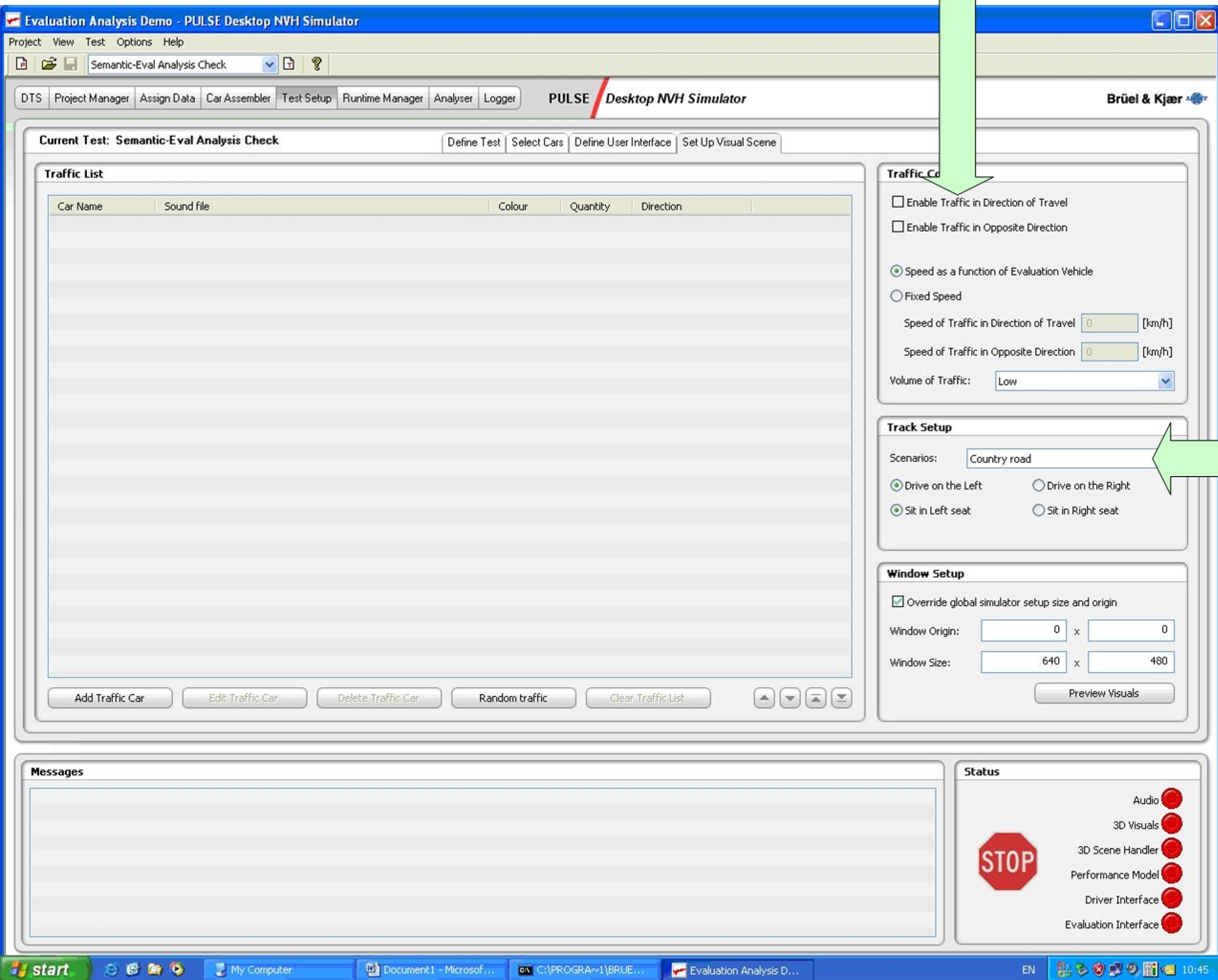
Introduce a better hierarchical model for HEV selection.


Additional HEV specific ICE information to include:
1. Engine size (l)
2. Max. peak power (kW)
3. Fuel type
4. ICE/Motor switching
5. EV only mode
Engine
Engine Size
| l
Max. Peak Power
| kW
Fuel Type
|Gasoline
ICE/Motor switching
|>30mph
EV only mode
Yes/No
Evaluation Analysis Demo - PULSE Desktop NVH Simulator
Project View Test Options Help
Semantic-Eval Analysis Check
DTS
Project Manager
Assign Data
Car Assembler
Test Setup
Runtime Manager
Analyser
Logger
PULSE
Desktop NVH Simulator
Brüel & Kjær
List of Car Models
Car Models
Sine 2000
Car Event Replay
Engine
Base Engine
Air Borne
Contributions
Structure Borne
Contributions
Engine Events
Start
Stop
Exhaust
Air Borne
Contributions
Structure Borne
Contributions
Intake
Air Borne
Contributions
Structure Borne
Contributions
Road
Sine 2000 Hz 70 dB
Front Road
Rear Road
Road Events
Wind
Leakage
Shape
Wind Events
Other
Ancillaries
Custom
Gears
Assemblies Overview
Evaluation Assemblies
Mixer Assemblies
Hierarchy Assemblies
Messages
Status
STOP
Audio
3D Visuals
3D Scene Handler
Performance Model
Driver Interface
Evaluation Interface
start
My Computer
Desktop Simulator Int...
C:\PROGRA~1\BRUE...
Evaluation Analysis D...
EN
10:52

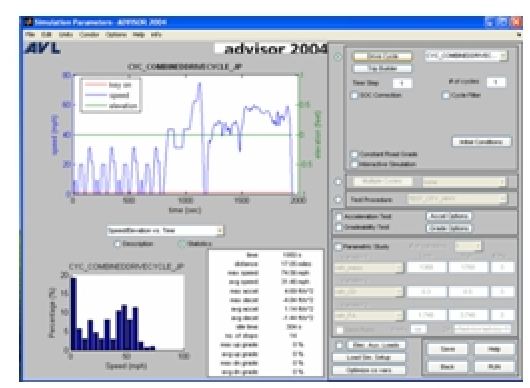


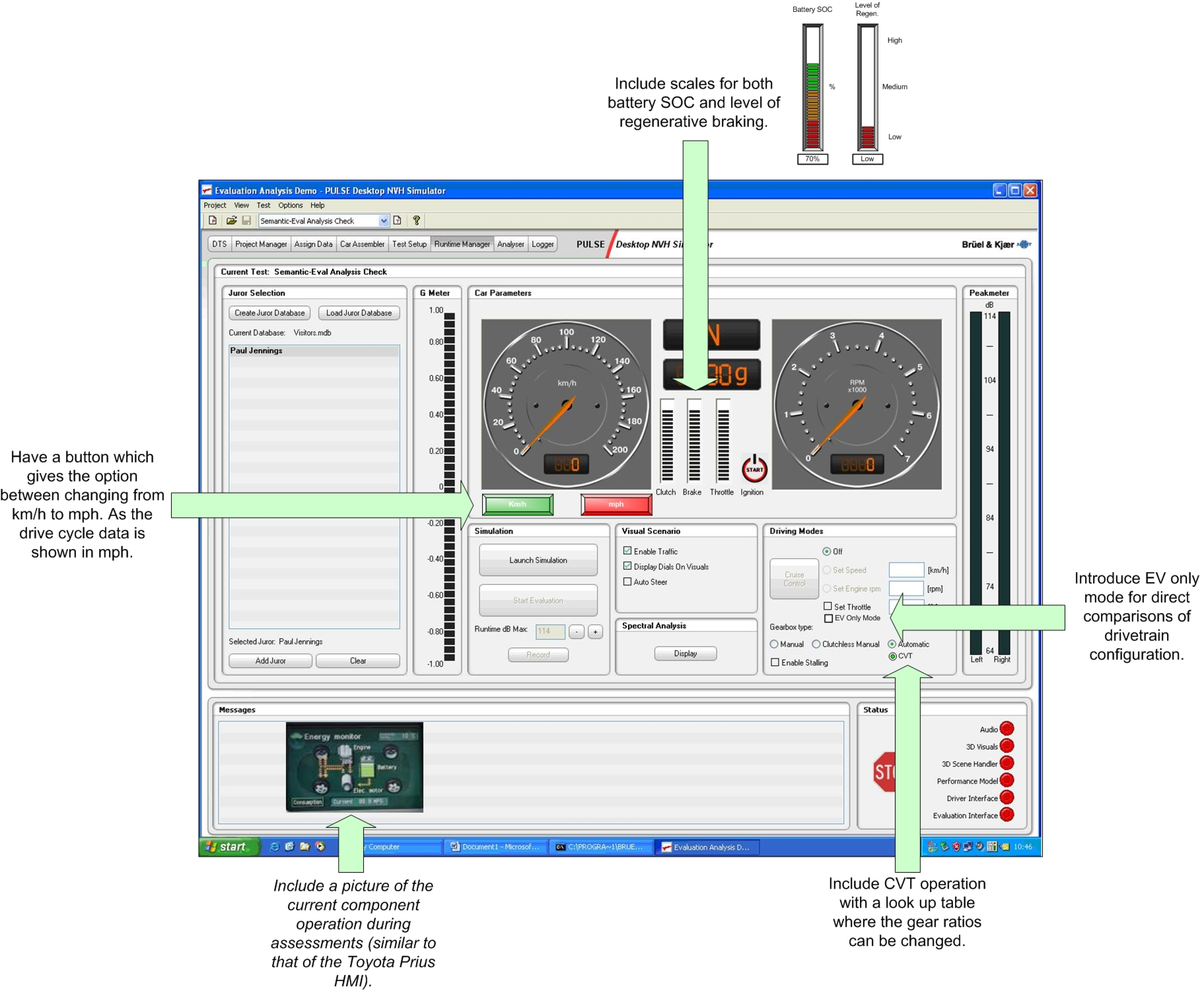
For free-drive assessments participants can be influenced in the way they drive through the introduction of traffic or speed limits. This could be used as a means to assess driver comfort, driveability and levels of regenerative braking for example.





Create new environments based on obtained data from real-world test tracks and standard emissions drive cycles.




Battery SOC
%
70%
Level of Regen.
High
Medium
Low
Low
Include scales for both battery SOC and level of regenerative braking.
Evaluation Analysis Demo - PULSE Desktop NVH Simulator
Project View Test Options Help
Semantic-Eval Analysis Check
DTS Project Manager Assign Data Car Assembler Test Setup Runtime Manager Analyser Logger
PULSE
Brüel & Kjær
Current Test: Semantic-Eval Analysis Check
Juror Selection
Create Juror Database
Load Juror Database
Current Database: Visitors.mdb
Paul Jennings
Selected Juror: Paul Jennings
Add Juror
Clear
G Meter
Car Parameters
km/h
RPM x1000
Clutch
Brake
Throttle
Ignition
Km/h
mph
Peakmeter
dB
Left
Right
Simulation
Launch Simulation
Start Evaluation
Runtime dB Max
Record
Visual Scenario
Enable Traffic
Display Dials On Visuals
Auto Steer
Spectral Analysis
Display
Driving Modes
Off
Cruise Control
Set Speed
Set Engine rpm
[km/h]
[rpm]
Set Throttle
EV Only Mode
Gearbox type:
Manual
Clutchless Manual
Automatic
CVT
Enable Stalling
Messages
Energy monitor
Status
Audio
3D Visuals
3D Scene Handler
Performance Model
Driver Interface
Evaluation Interface
Have a button which gives the option between changing from km/h to mph. As the drive cycle data is shown in mph.
Introduce EV only mode for direct comparisons of drivetrain configuration.
Include a picture of the current component operation during assessments (similar to that of the Toyota Prius HMI).
Include CVT operation with a look up table where the gear ratios can be changed.